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ABSTRACT

This technical specialty course is one of thirty-five courses designed for use by two-year postsecondary institutions in five nuclear technician curriculum areas: (1) radiation protection technician, (2) nuclear instrumentation and control technician, (3) nuclear materials processing technician, (4) nuclear quality-assurance/quality-control technician, and (5) nuclear reactor (plant) operator trainee. This course, Metallurgy and Metals Properties, contains eight modules: Fabrication Processes for Metals: Chemical Analysis of Metals: Basic Metallurgical Concepts: Properties of Steel: Metallographic Examination: Mechanical Testing: Tensile, Bend Hardness: Mechanical Testing: Impact Nick Break, Fatigue: and Failure Mechanisms in Metals. Each module follows a typical format including the following sections: introduction, module prerequisites, objectives, subject matter, exercises, materials, procedures, data tables, reference materials, and tests. (A master index and suggested program planning guides are also available--see CE 026 856 and CE 026 639-643.) (LRA)

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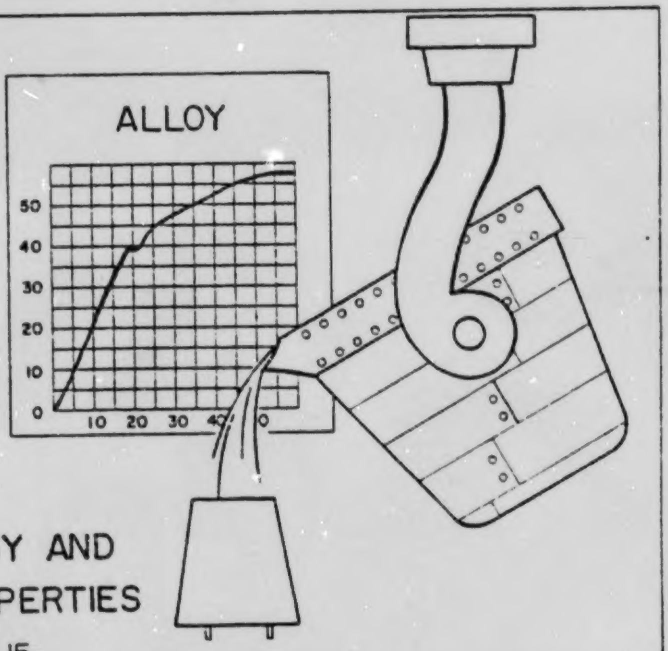
ED192098

NUCLEAR TECHNOLOGY

Series

MODULE 15-1 FABRICATION PROCESSES FOR METALS



METALLURGY AND
METALS PROPERTIES
COURSE 15

U.S. DEPARTMENT OF HEALTH.
EDUCATION & WELFARE
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COURSE MODULES

COURSE 15. METALLURGY AND METALS PROPERTIES

⇨ MODULE 15-1	Fabrication Processes for Metals
MODULE 15-2	Chemical Analysis of Metals
MODULE 15-3	Basic Metallurgical Concepts
MODULE 15-4	Properties of Steel
MODULE 15-5	Metallographic Examination
MODULE 15-6	Mechanical Testing - Tensile, Bend Hardness
MODULE 15-7	Mechanical Testing - Impact, Nick Break, Fatigue
MODULE 15-8	Failure Mechanisms in Metals

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INTRODUCTION

On a day-to-day basis, most technicians are in contact with metals in one form or another. It is necessary, therefore, for power plant personnel to have a general understanding of the origin, basic processes and terms used in the metals industry. Most of the emphasis in this course centers around ferrous metals, that is, metals made from iron.

MODULE PREREQUISITES

Student must have completed a course in basic inorganic chemistry.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. List major steps in the production of pig iron and, with a sketch, identify major parts of a blast furnace.
2. List and describe the three major steelmaking processes.
3. List six of the common elements used in steel; give a brief description of the metallurgical effects of

each on the steel products.

4. List and describe four elements used to produce an alloy steel; give their metallurgical effects on the alloy.
5. List and describe three of the more common methods used in the production of steel shapes or forms.
6. List and describe four terms (used in the steelmaking industry) relating to processes or products.
7. Prepare a simple, labeled flow diagram of the process used in producing:
    - Pig iron.
    - Steel plates.
    - Tubing.
    - Forgings.
8. Take apart a scrapped valve; identify material in each part, noting whether it is machined, forged, cast, or made by combination of processes.

The extraction of iron from ore can be traced to the times of the Great Pyramids of Egypt (built about 2900 BC). Crude methods of "smelting," in which iron-bearing ore was heated in contact with very hot coals, and caused the oxygen in the iron ore to combine with the hot coals, forming a spongy metallic iron.

The blast furnace process discovered around the year 1350, in central Europe, produced other forms of metal called "cast and wrought iron." Wrought iron is more refined and purified than cast iron; it has low carbon and high phosphorus content. The blast furnace is basically a shaft type of furnace in which solid fuel is burned with an air blast to smelt (or liquify) the metal into a useful ore in a continuous operation as will be considered in the next section which explains the blast furnace process.

The desire to produce iron products at a cheaper cost and at a greater volume envolved the modern blast furnace for the production of "pig iron". In this case, the temperature must be high. Therefore, the air is usually preheated. Where the temperature can be lower as in the smelting of copper, lead and tin ores, a smaller furnace is economical, and preheating of the blast is not required. The term "pig iron" comes from the method of pouring the hot iron into open sand beds arranged so that the main feed stream leads to a series of smaller molds as shown in Figure 15-1-1. Since this arrangement looked like a litter of suckling pigs, each individual mold was referred to as a "pig" and the main runner as a "sow." The composition of pig iron varies according to the process and iron ores used.

Iron is the first step in the manufacture of steel.

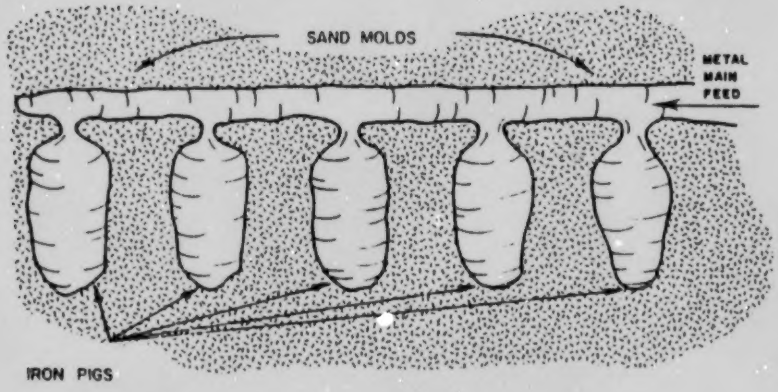


Figure 15-1-1. "Pig iron" casting in sand molds.

BLAST FURNACE PROCESS

A blast furnace uses four main ingredients:

Iron-bearing materials.
Fuel.
Flux.
Air.

Iron-bearing materials come in several forms. The most common are iron-bearing ores from the earth. Others include iron-ore pellets, and iron and steel scraps.

Fuel produces the heat for the smelting process. A material called "coke" performs as the most efficient and economic fuel. (Coal, dry distilled in an air-free system at high temperatures to remove moisture, becomes coke.)

Flux combines with the coke and other impurities to form a fluid slag; the slag controls chemical content of the final pig iron. The most common forms of flux used are limestone and dolomite.

Air introduced into the blast furnace provides combustion of the coke, and it controls the thermal operation of the furnace. (Sometimes, air and gas mixtures are used.) In the operation of a modern blast furnace, air is introduced at a temperature between 1400°F and 2100°F (Figure 15-1-2).

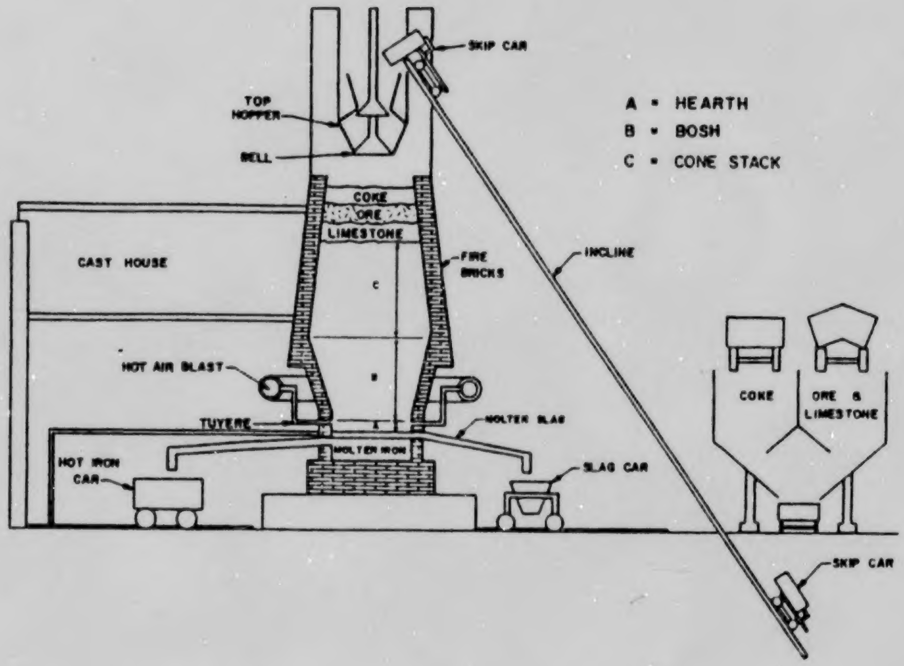

SKIP CAR
TOP HOPPER
BELL
A = HEARTH
B = BOSH
C = CONE STACK
COKE
ORE
LIMESTONE
CAST HOUSE
FIRE BRICKS
INCLINE
C
B
A
HOT AIR BLAST
TUYERE
MOLTEN SLAG
MOLTEN IRON
HOT IRON CAR
SLAG CAR
COKE
ORE & LIMESTONE
SKIP CAR

Figure 15-1-2. Modern blast furnace. (Metallurgy, C.G. Johnson and W.R. Weeks, American Technical Society, Chicago, 1977.)

STEEL PRODUCTION

Steel is a mixture (alloy)of iron and carbon. So is pig iron. But steel has a lower carbon content than pig iron (less than 0.2%); steel also contains other elements, such as 1% manganese, traces of phosphorus, sulphur, silicon and copper. By varying the percentage of these elements, the physical properties of steel products can be changed.

Steel is produced by three main processes:

Bessemer conversion.
Open hearth.
Electrical furnace.

Ninety percent of all steel produced in the U.S. is a product of the open-hearth process; the remaining ten percent is evenly distributed between Bessemer and electric-furnace processes. (Electric-furnace processes produce "super-alloy" steels, such as stainless, high-temperature tool steel, food-processing equipment steels and other special products.) These three processes will be considered as follows.

THE BESSEMER PROCESS

The Bessemer Process is a process for making steel by blowing air through molten pig iron contained in a large steel vessel or converter lined with a refractory material such as silica, clay or dolomite (a calcium and magnesium carbonate compound). The Bessemer converter makes it possible to produce large quantities of low grade steel in a fast, efficient, and economical manner.

Bessemer steel is made in a pear-shaped converter which is mounted on trunnions so that it can be tilted easily for charging and pouring as shown in Figure 15-1-3. Molten pig iron is poured into the converter and air is blown through the metal. It can be seen in Figure 15-1-3 that the air for the process is blown through one hollow trunnion and is distributed through tuyres (openings in the shell and refractory lining of the furnace).

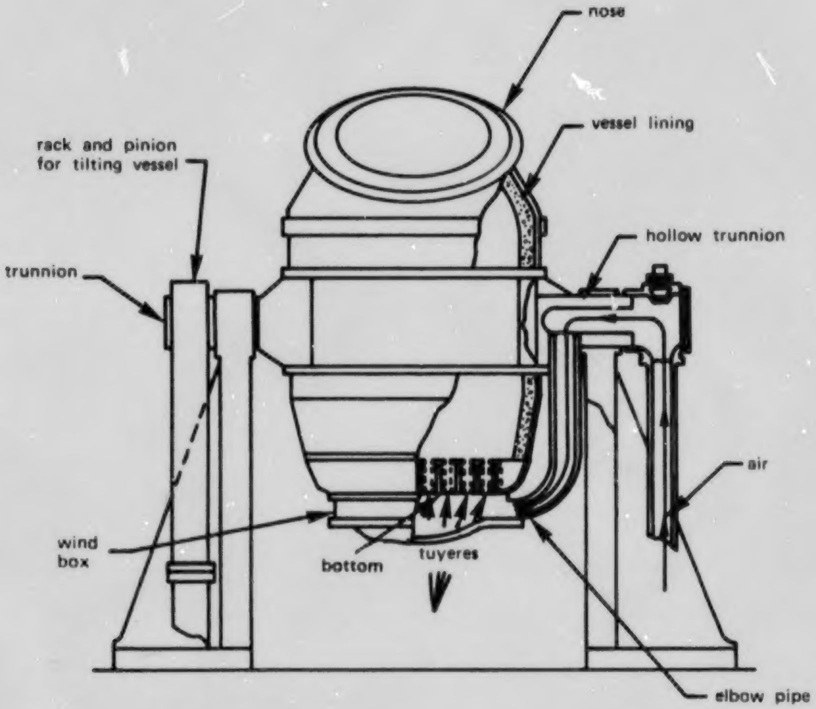

nose
vessel lining
rack and pinion for tilting vessel
hollow trunnion
trunnion
air
wind box
bottom
tuyeres
elbow pipe

Figure 15-1-3 Schematic Cutaway View of the Bessemer Converter (From U.S. Steel Corp., The Making, Shaping, and Treating of Steel, 7th Edition, 1957)

During a typical blow, the hot metal is charged while the vessel is tilted in the horizontal position, as shown in Figure 15-1-4 to keep the tuyres clear.

The air blast is turned on as the vessel is righted as shown in Figure 15-1-5. At this time the air bubbles up through the molten metal which is typically 18 to 24 inches in depth.

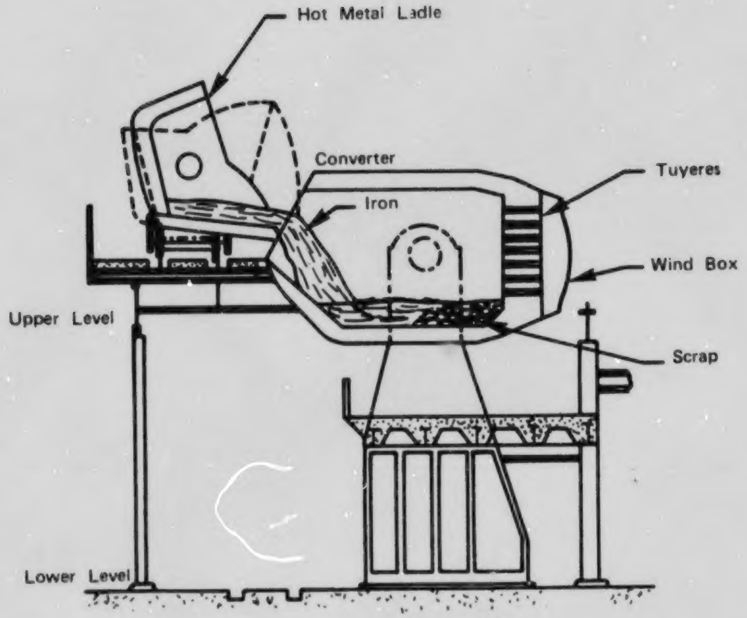

Hot Metal Ladle
Converter
Tuyeres
Iron
Wind Box
Upper Level
Scrap
Lower Level

Figure 15-1-4. Schematic Drawing of the Position of a Bottom-Blown Converter Showing Charging

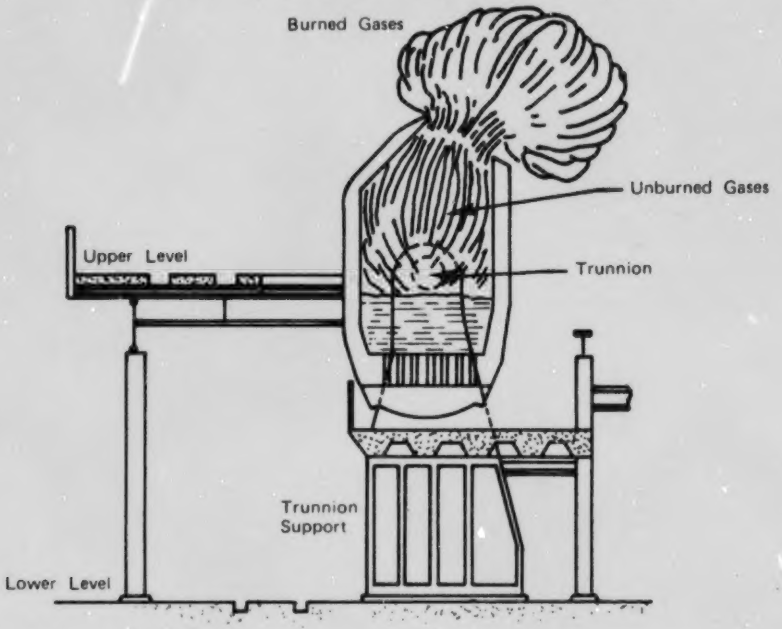

Burned Gases
Unburned Gases
Upper Level
Trunnion
Trunnion Support
Lower Level

Figure 15-1-5. Schematic Drawing of the Position in the Operation of a Bottom Blown Converter Showing the Air Blowing Operation

The high temperatures required for the Bessemer Process are produced and maintained by the oxygen which bubbles through the hot molten mass of metal contained in the converter. The oxygen oxidizes the impurities in the iron which results in the liberation of heat. During the oxidation process, the following refining reactions:

$$2Fe + O_2 \rightarrow 2FeO \quad \text{(slag)}$$
$$2Mn + O_2 \rightarrow 2MnO \quad \text{(slag)}$$
$$Si + O_2 \rightarrow SiO_2 \quad \text{(slag)}$$
$$2C + O_2 \rightarrow 2CO$$

The reactions occur approximately in the order listed above. They are exothermic (that is, they liberate heat) and provide enough heat to raise the temperature of the charge (about $1350^{\circ}C$) to that of the product (above $1600^{\circ}c$). This temperature rise serves to make the Bessemer Process an efficient one. In addition the temperature rise can be controlled by the regulation of the hot-metal analysis (Silicon content being the most important) and the amount of scrap added during the blow. When carbon has been nearly eliminated, the method is recarburized by the addition of alloys containing carbon, manganese, and silicon. Typically, from 8 to 30 tons of steel can be made in one blow requiring only 10 to 20 minutes by means of the Bessemer Process.

The flame emitted from the mouth of the vessel changes color and luminosity in a manner which allows the operator to judge the progress of the refining reactions, to stop the operation at a suitable end point, and to pour the heat into a transfer ladle by tilting the vessel as shown in Figure 15-1-6.

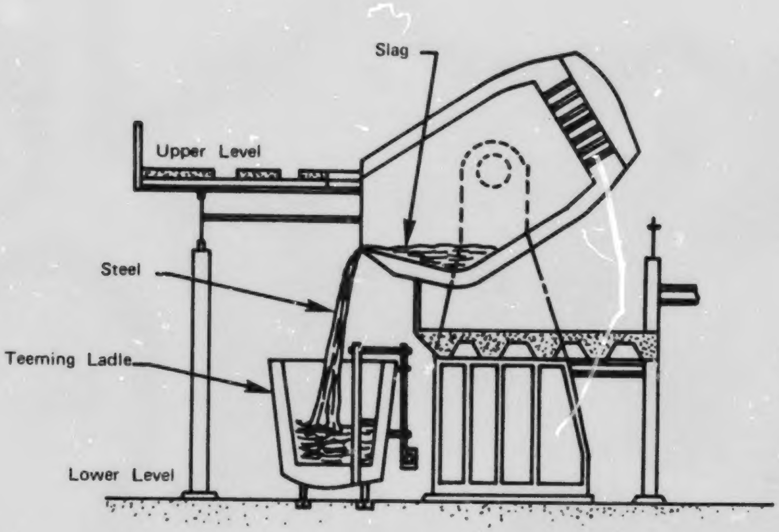


Figure 15-1-6 Schematic Drawing of the Positions in the Operation of a Bottom-Blown Convertor showing the Pouring Process.

THE OPEN HEARTH PROCESS

The basic open hearth process has been major method for producing steel in the United States ever since the beginning of the 20th century. The process produces a finer quality of steel than that produced by the Bessemer method. It was developed by Sir William Siemens in about 1858. The open hearth process consists of a shallow bed lined with magnesium oxide. A producer gas, burning fiercely, is introduced from one of two sides of the furnace as shown in Figure 15-1-7.

The direction of the flow of gas and air is reversed at certain intervals ensuring that the mixture always enters the furnace in a pre-heated condition. This is known as the regenerative principle; it allows the attainment of extremely high temperatures inside of the furnace.

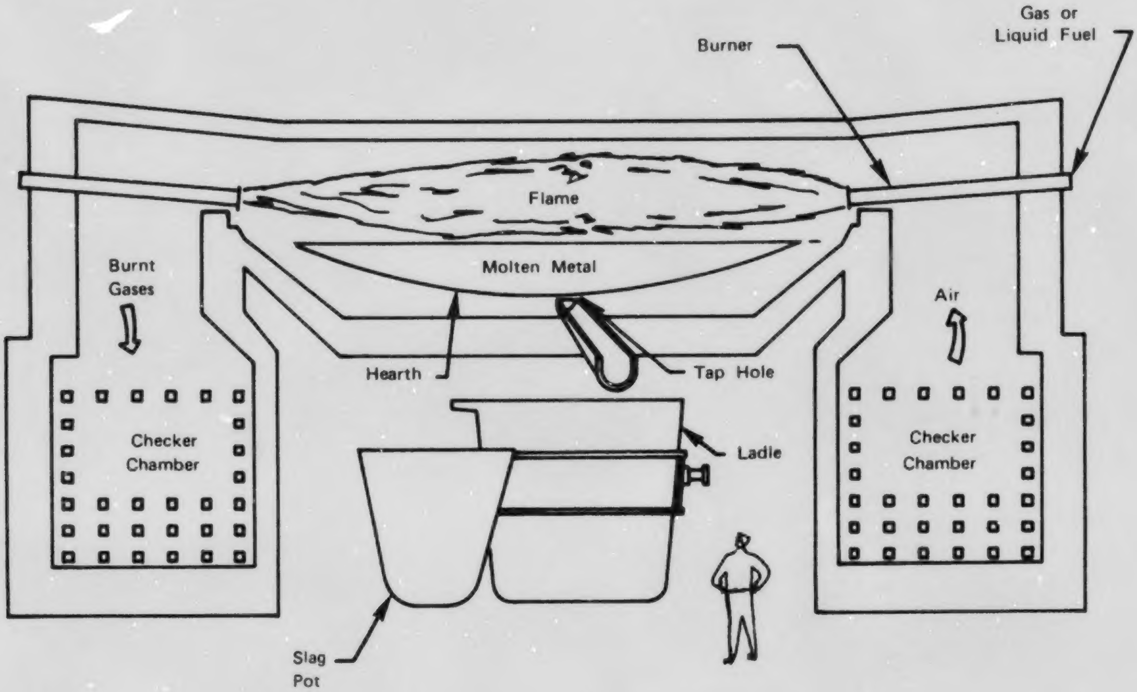

Gas or
Liquid Fuel
Burner
Flame
Molten Metal
Burnt
Gases
Air
Hearth
Tap Hole
Checker
Chamber
Checker
Chamber
Ladle
Slag
Pot

Figure 15-1-7 Schematic Diagram of an Open Hearth Furnace. Charge of molten steel in basin-shaped hearth is heated by mixutre of gas and air. Burnt gases flow through checker chambers (regenerators). Direction of flow is reversed about every fifteen minutes. (Courtesy of Bethlehem Steel Co.)

Open hearth steel has a wide variety of uses; it is in much demand in the manufacture of armor plate, railroad tracks, and steel girders, when structural work requires steel of an exceptional strength.

Although the open hearth process has been the predominant method used for steel production during the century, new steel mills currently being built utilize some variation of oxygen steel making or electric furnaces. Therefore, the classic open hearth process may not survive as the principal source of steel in the years to come.

ELECTRIC FURNACE PROCESS

This is a relatively new method of producing steel in comparison to the Bessemer and Open Hearth Processes. Electric melting actually began exerting its influence in the industry about 1900.

The electric furnace develops the necessary temperatures for steel production without the requirement of oxygen in the atmosphere. As a result, this process occupies a unique position as a process suitable for making many grades of steel with large amounts of such oxidizable alloys as chromium, vanadium and tungsten. Beginning with the original design of Paul L.T. Héroult, the three-electrode furnace has been developed to the point where it is competing with the open-hearth process for all grades of steel and consequently, it appears destined for a continued increase in importance. The features of the electric arc furnace are shown in Figure 15-1-8.

Figure 15-1-8 also indicates the differences in refractories for basic or acid practice. Heavy graphite electrodes are suspended from the roof and the furnace itself is placed on rollers so that it can be moved when its contents are about to be emptied. As in the open hearth method, the solid charge of iron ore, limestone, scrap and pig iron is placed in the hearth after the previous heat has been drained and the bottom repaired. The amounts of these materials are proportioned to achieve the desired specifications when the charge has been melted and brought to temperature; mainly, enough oxygen is provided to refine the silicon, manganese, phosphorous and carbon present in the charge, and enough lime is included to give the slag basicity required to retain phosphorous in the slag. Air within the furnace is in contact with the graphite electrodes

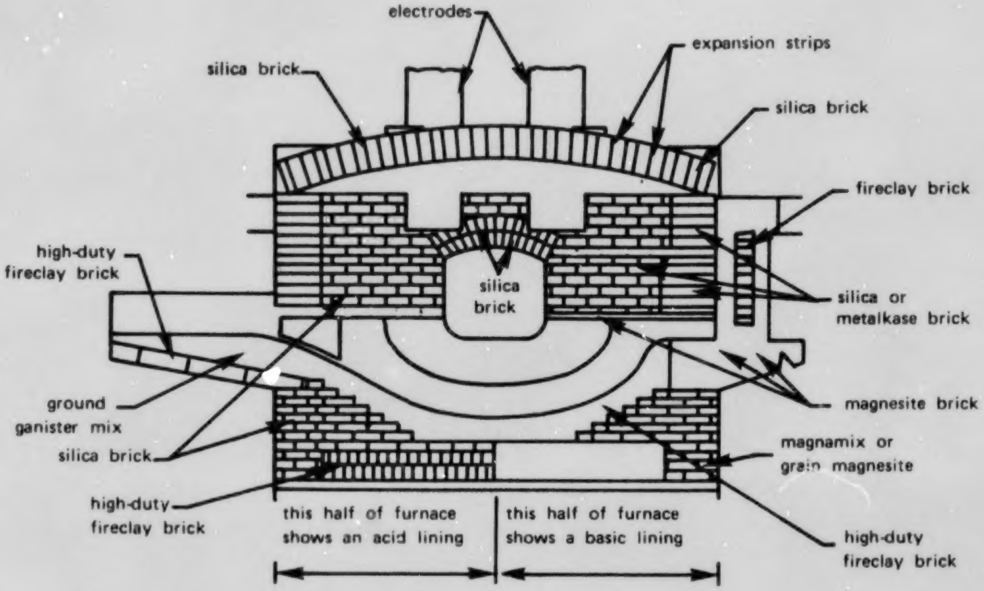

electrodes
silica brick
expansion strips
silica brick
fireclay brick
high-duty fireclay brick
silica brick
silica or metalkase brick
ground ganister mix
magnesite brick
silica brick
magnamix or grain magnesite
high-duty fireclay brick
this half of furnace shows an acid lining
this half of furnace shows a basic lining
high-duty fireclay brick

Figure 15-1-8. Section of an Electric-Arc Furnace Showing Refractories of either Acid or Basic Operation. (Courtesy of Modern Refractory Practice, Harbison-Walker Refractories Co.)

as shown in Figure 15-1-8. Hence, all oxygen is rapidly burned to the Co-Co$_2$ equilibrium for the furnace temperature. The basic oxidizing slag will contain phosphorous refined from the charge, so this slag can now be removed from the system, the furnace being tilted to assist in this operation.

The steels produced by an electric arc furnace contain an appreciably higher nitrogen content than the same grades made in the open-hearth process. This may or may not be desirable based upon its intended use.

TABLE 15-1-1

CERTIFICATION OF U.S. STEELMAKING PROCESSES

Process	Raw Material Used	Percentage present in finished steel		Furnace slags remove			Principal products
		Phosphorus	Sulphur	Phosphorus	Sulphur	Oxygen	
Basic open hearth	Scrap and pig iron	0.020 to 0.045	0.030 to 0.055	Most	Part	Very little	Structural shapes, plate, sheet, strip, rails, tubes, wire, and large castings of carbon and alloy steels
Acid Bessemer	Molten pig iron	0.070 to 0.12	0.030 to 0.065	None	None	None	Skelp for pipe, sheet bar for tinplate, some wire and zinc-coated sheet, free-machining steels
Basic electric	Scrap	0.010 to 0.035	0.010 to 0.030	Most	Most	Most	Special alloy steels, high-grade carbon steels, special tool steels, and high-speed steel
Acid open hearth	Scrap and pig iron	0.040 to 0.065	0.020 to 0.045	None	None	Part	Large castings, high-strength wire, large forgings, ordnance, and armor plate
Acid electric	Scrap	0.030 to 0.065	0.020 to 0.045	None	None	Part	Small carbon and alloy castings, and a few special alloy steels

COMMON ELEMENTS IN STEEL

In addition to the most important element, carbon, commercial quality steel contains varying amounts of other elements:

Manganese.
Silicon.
Sulphur.
Phosphorus.
Copper.
Nickel.
Chromium.
Molybdenum.
Lead.
Arsenic.
Aluminum.
Tin.

Trace Elements

Also, there may be small percentages of oxygen, nitrogen and hydrogen. Some of these elements are added intentionally to obtain specific steel properties; most are absorbed during production processes.

Carbon

Carbon has a marked effect on the properties of steel and, when approximately 0.1% of carbon is continuously added, four things happen to the material: the steel gets harder, its strength (tensile) increases, its stretch (ductility) decreases and its weldability decreases.

Carbon, like oxygen, sulphur and phosphorus, has a tendency to disperse throughout the steel in a nonuniform manner. But, because of its major effects on steel properties, its disposition is far more important than for other elements.

Manganese

Manganese, in a similar manner, but to lesser degree than carbon, contributes to the hardness and strength of steel but decreases its ductility and weldability. Manganese combines with sulphur, thereby reducing the formation of FeS, which improves the "hot shortness" of the steel. When manganese content of a steel exceeds 1.65%, it is classified as an alloy steel.

Silicon

Silicon, like manganese, is beneficial when added to carbon steel. It acts to remove oxygen and reduce the formation of elongated stringers in the rolled material.

Sulphur

Except when machinability is of prime importance, sulphur is generally considered to be an undesirable element in steel. Sulphur combines with iron to form iron sulphide (FeS) particles that dissolve in molten iron. These particles, known as "inclusions" or "dirt" in the steel, can causes brittleness or cracking when the steel is raised in temperature for hot working or hot forming. The process whereby brittleness can occur in the metal in those hot forming operations such as bending, drawing, forging, piercing and pressing above the recrystallization temperature is called "hot shorting."

Recrystallization is the change from one crystal structure to another, as that which can occur during heating or cooling through a "so-called" critical point. (The temperature-pressure combination at which a change in crystalline structure occurs.)

Phosphorus

Phosphorus combines with the iron in steel to form iron phosphide (Fe_3P), which dissolves in solid iron much as sugar dissolves in water.

From 0.07% to 0.12% phorphorus content causes cold steel to be brittle ("cold short"), allowing no resistance to impact. This cold-short property is also affected by the amount of carbon present.

Engineering specifications usually indicate a phosphorus limit, ranging from 0.12% for low-carbon steels to 0.045% for high-carbon steels.

Copper

Copper is a trace impurity also found in carbon steel. Because it typically falls into the range between 0.10% and 0.30% in most carbon steels, it is often neglected as an impurity. However, its presence in steel used for nuclear reactor vessel is of significant importance as is discussed in Module 30-7, Pressure Vessel Inspection.

The fast neutron irradiation effects produced in the reactor vessel knock copper atoms from their crystalline lattice position more readily than the iron atoms. As a result, the reactor vessel tends to be more prone to brittle fracture due to the crystalline lattice damage.

Oxygen

Steel, with the exception of that produced by an electric-furnace process, is in constant contact with gases and slags. This contact allows oxygen to combine with carbon, iron, manganese and other elements, forming a variety of gaseous and liquid oxides. When an ingot is poured, these inclusions may be trapped in small round particles (sometimes visible to the naked eye). When an ingot is heated for rolling into flat sheets, these inclusions become soft and form stringers of "dirt," elongated in the direction of rolling. These stringers may cause the steel to have directional-strength properties.

KILLED AND RIMMED STEELS

"Killed" steels are free of gas cavities. Their name derives from the fact that, when molten metal is poured into an ingot, the metal lies perfectly still (killed). These steels are degasified by adding silicon and aluminum. They are used for forging high-carbon tools and springs.

Rimmed steel (Figure 15-1-9) derives its name from a series of blow holes placed around the edge (rim) of an ingot during cooling. The holes are far enough from the edge to close up during the hot rolling process thus rendering the metal virtually free of voids. Sheet and strip products made from this ingot have a very good surface quality. These steels are particularly suitable for automobile bodies and fenders.

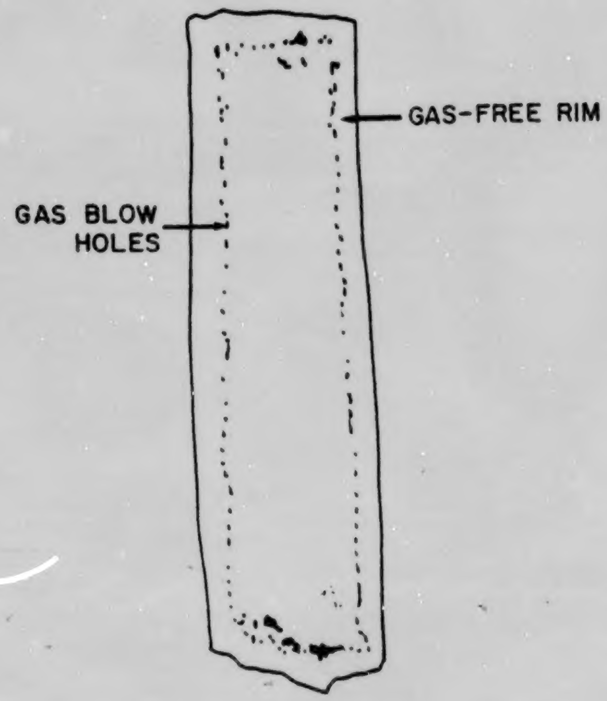


Figure 15-1-9
Cross section of a rimmed ingot.

ALLOY STEELS

Alloy steel is any steel to which elements not present in carbon steel have been added to achieve special desired properties. There are two classes of alloy steels: 1) low-alloy engineering steels and 2) high-alloy steels (tool and die). The latter is corrosion and heat resistant, and considered to be special purpose alloys but the second class is especially suited to today's nuclear and machine age needs.

Alloy steels are more difficult to produce than carbon steel (and, therefore, are more expensive) for the following reasons:

Chemical composition tolerances (of the elements) are closer.

Number of ingredients is increased.

Chances of spoiled melts are greater.

Expensive secondary, controlled-cooling equipment is required.

Poured billets produce more waste (because offcuts of nonusable material are necessary).

In process inspections and final testing are more extensive and rigid.

The most commonly used alloy elements include:

Nickel.
Chromium (chrome).
Molybdenum (moly).
Vanadium.

Nickel

Nickel, when used in appreciable amounts, provides:

Improved strength at low temperatures.

- Improved corrosion resistance.
- Better response to heat-treating procedures.
- Additional material strength with lower carbon content.
- Improved casehardening (hardening on the outside) for such items as aircraft engine gears and roller bearings.

Chromium

Chromium (chrome), when used in correct proportions, imparts the following properties to an alloy:

- Increased ability to harden the inside of a thick section of metal, such as a large forging.
- Wear resistance.
- Improved corrosion resistance.

Molybdenum

Molybdenum (moly) provides the following beneficial effects when used in an alloy:

- Improves "hardenability."
- Permits close hardenability control.
- Increases high-temperature strength (of alloy).
- Improves metallurgical property called "creep strength."
- Improves corrosion resistant material, when used with other alloying elements such as chrome or nickel.

Vanadium

Vanadium is used to obtain a more refined (smaller) grain size in steels. Also, when added to constructional steels, it improves their mechanical properties. Vanadium is also used with other alloying elements to produce such items as chrome-vanadium spring steels, manganese-vanadium forgings, manganese-vanadium steel plates, vanadium tool steels and vanadium die steels.

When more than one of the above elements are used in an alloy steel, it is called a double or triple alloy. When used in such a combination, the resulting steel usually provides better properties than if only one alloying element is used.

SHAPING OF STEEL

Mechanical shaping of steel is the permanent change of the shape of a metal by application of mechanical forces at its boundaries. In a blacksmith shop, for example, both cold and red-hot metals are pounded with a heavy hammer to create useful shapes: the plastic working of metal can be performed by "hot working" and "cold working" processes.

Metals are made up of grains or crystals of materials (Figure 15-1-10). A mechanical force applied to this metal

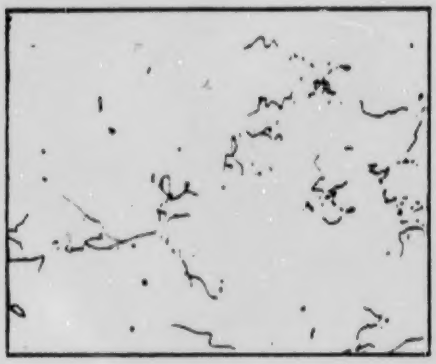


Figure 15-1-10.
Micrograph of a steel specimen with no force applied.
(2500X).

might cause it to stretch (Figure 15-1-11). Because grain size is only 0.01" to 0.001" in diameter, total stretch is small. If the mechanical force is increased, the grains move or slip and the whole shape is permanently changed.

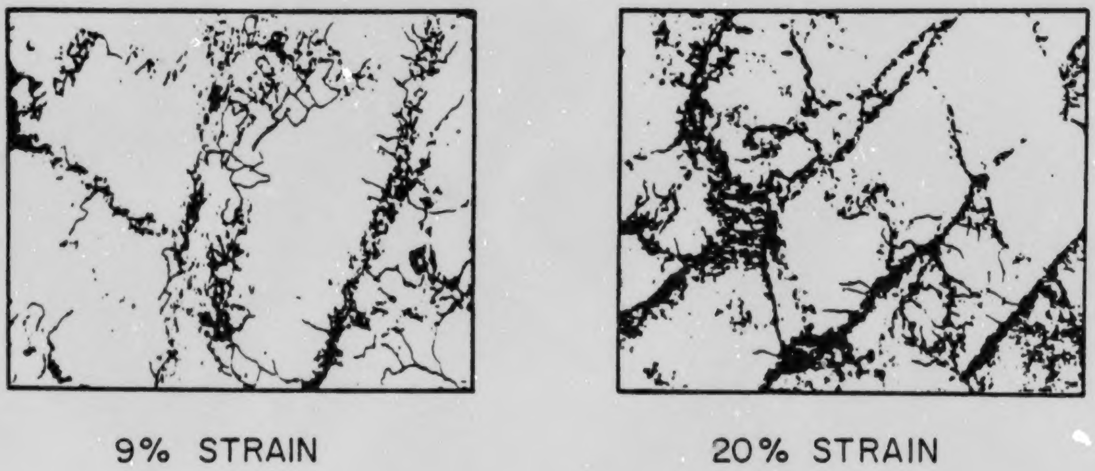


Figure 15-1-11. Micrographs of a steel specimen with forces applied (2500X).

HOT-WORKING METHODS

Steel can be formed into different shapes by pressing, hammering, rolling or squeezing (extruding) the hot metal. The steel industry associates the term "forging" with pressing (Figure 15-1-12) and hammering operations.

Hammering operations may be carried out in a similar press, except that the hydraulic piston is double acting and applies repeated blows to the hot metal until it is forced into the desired shape. This method is particularly suitable in the production of round bars for steam turbine blades and shafts.

Mechanical forging, used extensively in small shops, is a process by which pressure on the upper die is applied by mechanical linkage from the arm of a crankshaft instead of a hydraulic piston. An electrically driven flywheel connected to the crankshaft, through a clutch device, returns the upper die for the next downstroke.

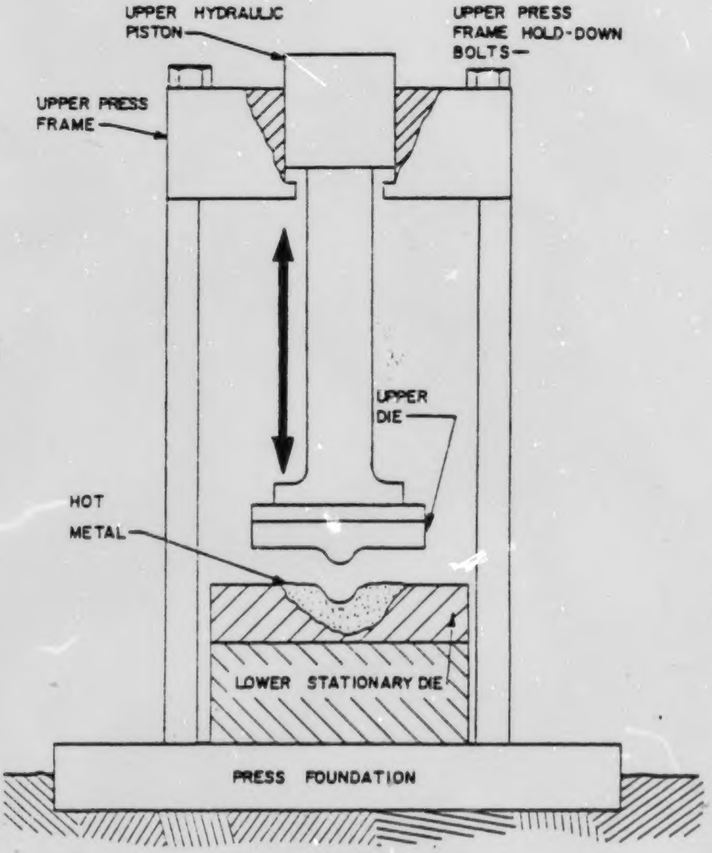

UPPER HYDRAULIC PISTON
UPPER PRESS FRAME HOLD-DOWN BOLTS
UPPER PRESS FRAME
UPPER DIE
HOT METAL
LOWER STATIONARY DIE
PRESS FOUNDATION

Figure 15-1-12.
Hydraulically operated
forging press.

Hot rolling (Figure 15-1-13) is the most extensively used method of shaping steel today; records show that, as far back as 1550, European plants were using such rolling processes.

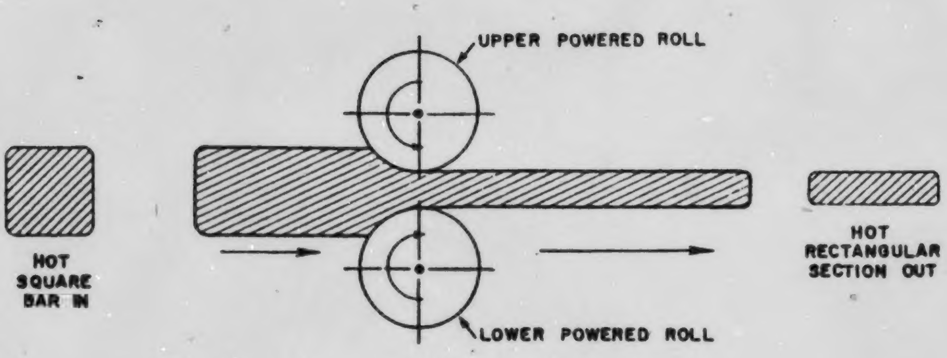

UPPER POWERED ROLL
HOT SQUARE BAR IN
HOT RECTANGULAR SECTION OUT
LOWER POWERED ROLL

Figure 15-1-13. Hot rolling of metal.

One metallurgical effect of hot rolling is production of a material with good strength properties: the metallic grains are small, uniform in size and located within the material in a uniform direction (Figure 15-1-14). As the

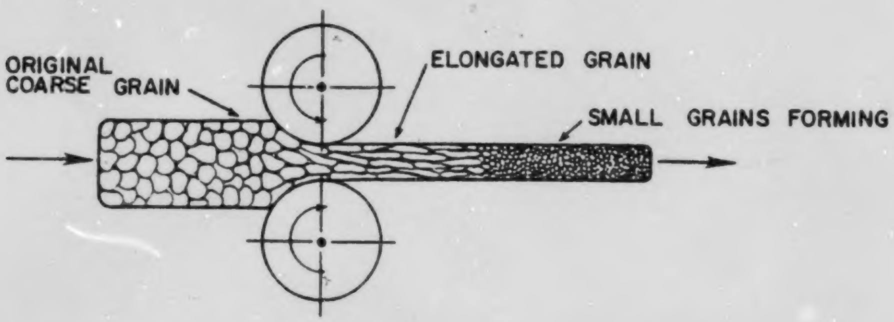

ORIGINAL COARSE GRAIN
ELONGATED GRAIN
SMALL GRAINS FORMING

Figure 15-1-14. Hot-rolling metal showing elongation and growth of grains.

hot plate is forced between the rollers, thickness is reduced and width increased. Large grains are not only broken up into smaller pieces, but they are all elongated in the direction of rolling. Because of the uniform high rolling temperature, small grains begin to form, which gives the material increased strength properties - smaller grain size means increased material strength.

COLD-WORKING METHODS

Cold-working methods are generally applied to bars, wires, tubes, and sheet and strip metals. This method is used to obtain specific improvements in the material:

Better mechanical properties.
Better machinability.
Special sizing of finished parts.
Special surface finishes.
Very thin gage material.

Cold-rolling processes pass bars through a series of rolls to obtain final sizing. Cold drawing (extrusion) is the term used when a bar, tube, rod or wire is pulled through a smaller orifice to achieve the required size as shown in Figure 15-1-17 of this module. Cold extrusion consists of placing a piece of cold metal in a closed container, with an extrusion die hole in one end and a pressure applied on the opposite end. The metal is forced through the die hole into a desired shape.

STEEL-MILL PRODUCTS

Terms to denote sizes of unfinished stocks of metals used in steel-mill industries are traditional. There are no precise definitions for such terms as "slab," "billet" or "bloom," but typical cross sections and dimensions for these terms do exist (Figure 15-1-15). These shapes are generally produced by hot rolling ingots or molds.

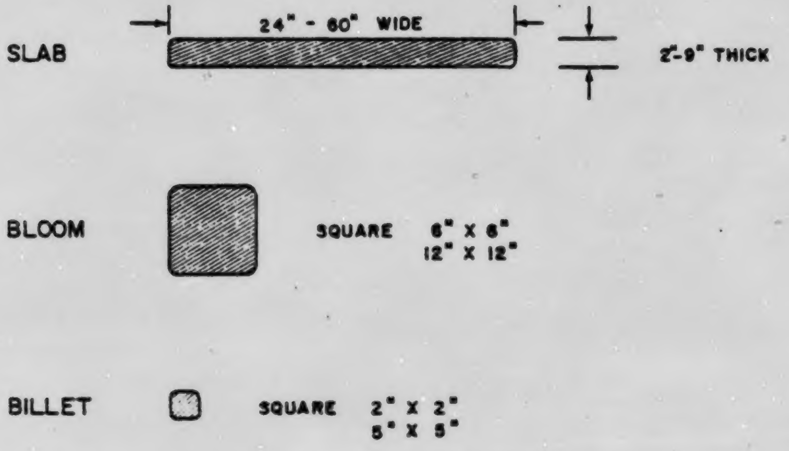


Figure 15-1-15. Typical cross sections.

Developments in steel-mill technology have resulted in techniques for continuous casting of molten metals into slabs and billets (eliminating the ingots, molds and hot-rolling operations); however, the traditional mills still produce more tonnage than continuous-casting mills.

A series of routine steps are used to convert cast steel ingots into rolled steel products. One is to reduce the size of the steel ingot by progressive rollings.

STEEL PLATE PRODUCTION

Steel plate is classified as flat, hot-rolled material, generally 0.25" thick (or thicker) x 8" to 48" wide, or 0.18" and thicker x over 48" wide.

HEAT TREATING

Heat treating is the heating or cooling of a solid metal or alloy in such a way so as to obtain certain desired conditions or properties. In general, two types of metal preheating are used. In the "batch" type, all the material is placed in a furnace as a bath, heated for a predetermined time, then removed. In the "continuous" type, cold metal is fed into the furnace at one end and, as it moves through the furnace, gas burners heat it to its rolling temperature.

(Certain grades of carbon and alloy steel require a heat-treating process to impart certain properties to the finished material. This subject is covered in Module 15-2, "Chemical Analysis of Metals.")

Basic heat treating terms include:

Annealing: a heating and cooling process used to soften a rolled plate to prevent it from cracking.

Normalizing: a process of heating rolled plate above a specific temperature, followed by air cooling, to improve properties of the plate.

Stress relieving: a process of heating the rolled plate to a lower specific temperature than when normalizing, to relieve internal stresses placed in the material by mechanical operations (cutting, cold working, shearing).

Spheroidize annealing: a process similar to stress relieving, except that cooling is carried out in a controlled cooling furnace to improve deep drawing capability of the metal.

Sizing plates: after all processing has been completed and quality-control checks have been made and accepted as satisfactory, heat-treated plates are moved to one of two sizing areas (shearing and trimming bay, or flame-cutting bay) where they are cut to final sizes, inspected again and shipped.

STEEL WIRE

Steel wire comes in many different forms and shapes, also composition, heat treatments and coated finishes.

Billets are heated in a furnace (Figure 15-1-16) and moved to a multistage rolling mill where each billet is reduced in cross-sectional area, which elongates it. After passing through the finishing rolls, the wire rods are coiled

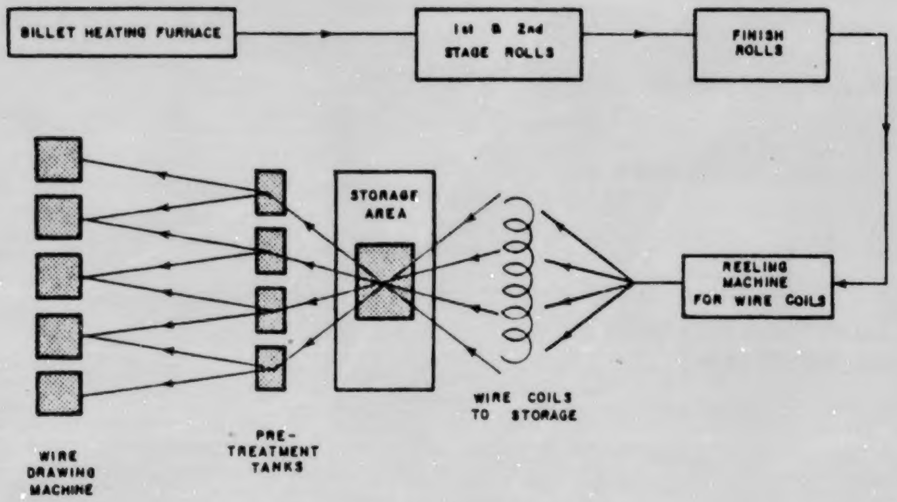

BILLET HEATING FURNACE
1st & 2nd STAGE ROLLS
FINISH ROLLS
STORAGE AREA
REELING MACHINE FOR WIRE COILS
WIRE COILS TO STORAGE
PRE-TREATMENT TANKS
WIRE DRAWING MACHINE

Figure 15-1-16. Wire mill.

onto reels and stored. Because of the large volume of stored wire rod, it is essential that care, inspection and maintenance of the wire rod manufacturing equipment be emphasized. Uniform composition, accuracy in cross section and freedom from internal defects are essential if the wire drawing phase is to run smoothly.

Before reels of wire rod are mechanically processed, they must be given extensive pretreatment consisting of acid cleaning and appropriate heat treatment. Then the wire is coated to prevent rusting in the atmosphere, to neutralize any acid solution that may have escaped the high-pressure spray and to provide a base for the wire-drawing lubricant.

When wire rod is reduced in cross section, this reduction in area is expressed as a percentage of the original area, called the "draft."

The end of the wire rod is tapered so that it will pass through the small hole in the center of the die. Lubricant is placed on the entering side of the die. Tongs grasp the tapered end of the wire and pull it through the die where it is connected to a draw-bar carriage. As the draw-bar carriage moves along, it pulls the wire rod through the die (Figure 15-1-17).

Wire drawing is a cold-working process; mechanical properties of the wire such as strength, hardness and stiffness are increased, while ductility is decreased.

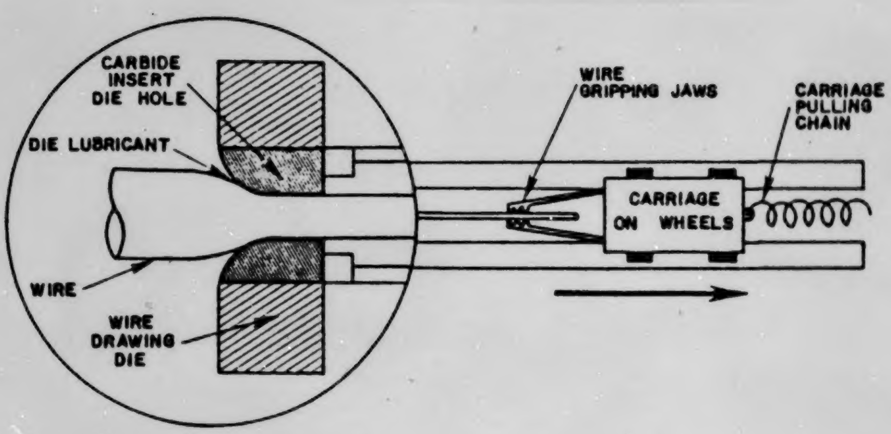

CARBIDE INSERT DIE HOLE
DIE LUBRICANT
WIRE
WIRE DRAWING DIE
WIRE GRIPPING JAWS
CARRIAGE PULLING CHAIN
CARRIAGE ON WHEELS

Figure 15-1-17. Wire draw bench.

STEEL TUBULAR PRODUCTS

Steel tubular products fall into approximately twenty different categories, each bearing about ten subdivisions. Mention can only be made of a few important categories and methods of manufacture.

BUTT-WELDING CONTINUOUS PROCESS

In the "continuous" process, a finished tube or pipe is manufactured from a flat strip of steel called a "skelp." The skelp is rolled in a longitudinal direction, and the closing seam is butt-welded (Figure 15-1-18).

FLASH WELDING

Flash welding is generally used to produce large diam-

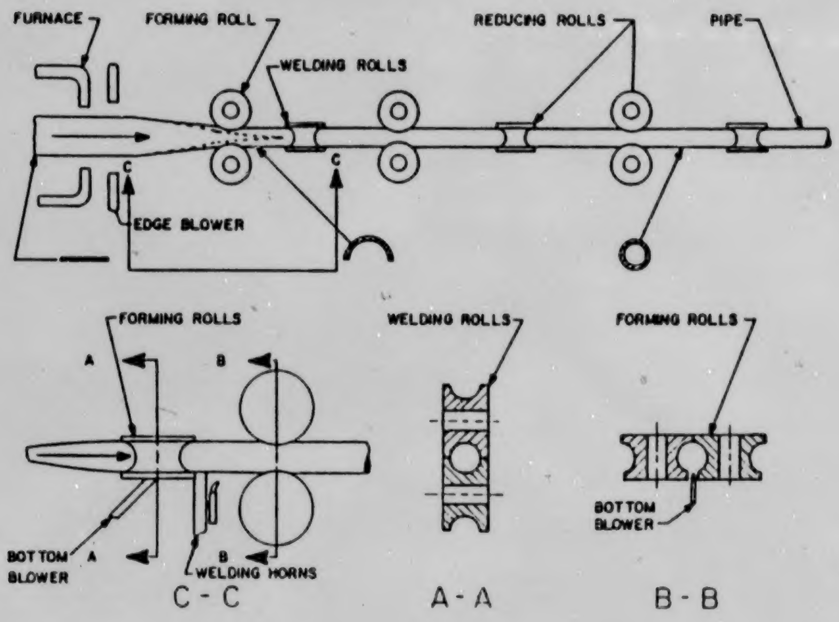

FURNACE
FORMING ROLL
WELDING ROLLS
REDUCING ROLLS
PIPE
C
C
EDGE BLOWER
FORMING ROLLS
A
B
BOTTOM BLOWER
A
B
WELDING HORNS
WELDING ROLLS
FORMING ROLLS
BOTTOM BLOWER
C - C
A - A
B - B

Figure 15-1-18. Continuous forming and welding.

eter pipes. In this process, a rectangular length of skelp is placed into the forming press and bent up to form the pipe in a Uing and an Oing machine (Figure 15-1-19).

ELECTRIC RESISTANCE WELDING

Tubing, manufactured by an electric-resistance welding process, is called ERW tubing. The development and use of nondestructive testing, such as ultrasonic and eddy-current techniques, have allowed ERW products to be accepted as quality products.

Four main steps comprise the ERW process:

Preparing steel strip.

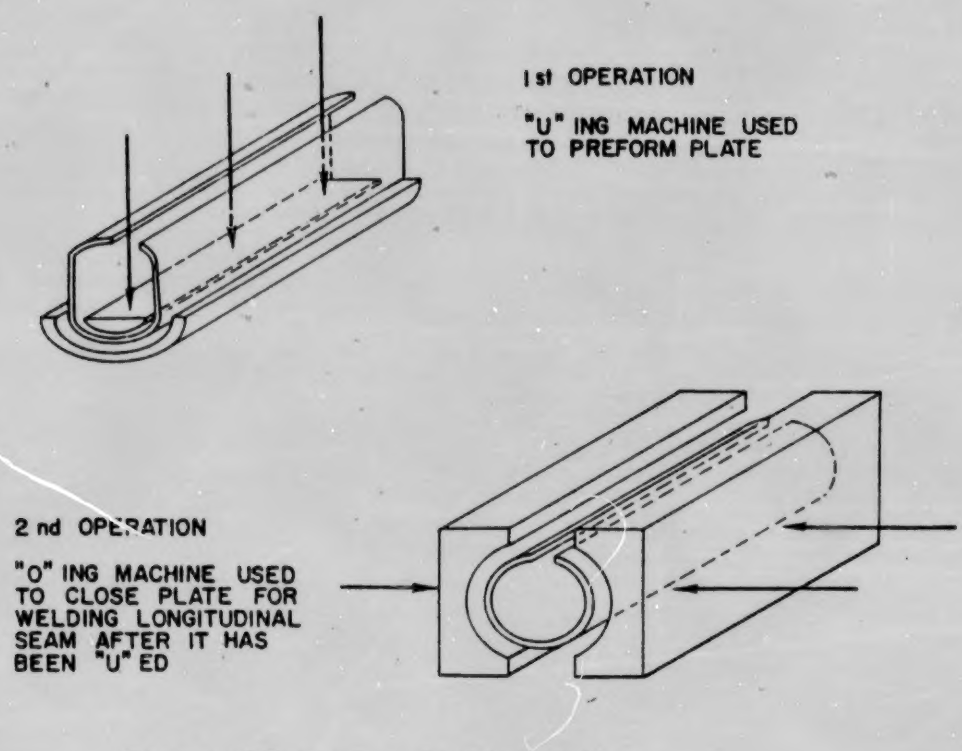

1st OPERATION
"U" ING MACHINE USED TO PREFORM PLATE
2nd OPERATION
"O" ING MACHINE USED TO CLOSE PLATE FOR WELDING LONGITUDINAL SEAM AFTER IT HAS BEEN "U" ED

Figure 15-1-19. Flash welding.

Forming strip into round tube.
Welding round tube.
Finishing tube.

Strip steel is passed into a series of forming rolls (Figure 15-1-20) where it is progressively rolled into a cylinder and fed into the welding pressure rolls. Welding is performed through low frequency power by the wheel, which acts as an electrode.

SEAMLESS MANUFACTURE

Seamless tubing has many uses in twentieth century industrial applications because it can be fabricated without

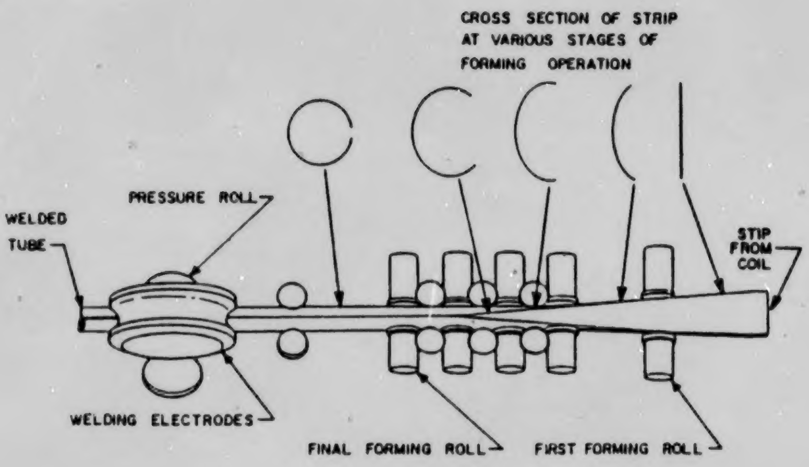

CROSS SECTION OF STRIP AT VARIOUS STAGES OF FORMING OPERATION
PRESSURE ROLL
WELDED TUBE
STIP FROM COIL
WELDING ELECTRODES
FINAL FORMING ROLL
FIRST FORMING ROLL

Figure 15-1-20. Cross section of strip at various stages of ERW forming operation.

a longitudinal weld seam, thereby increasing its strength capacity. Patented processes in use all have several common basic features, independent of hot- or cold-working methods:

Initial hot-forged billet.
Internal piercing device.
External sizing rolls.
Finishing processes.

Seamless tubing is made by piercing a round billet with an internal mandrel (Figure 15-1-21).

Cold-finished seamless tubing has several advantages over hot-finished tubing:

It can be produced in smaller diameters.
It can be produced in greater lengths.
It can be produced with thinner walls.
It can be produced with closer dimensional tolerances.
It can be produced with better surface finishes.

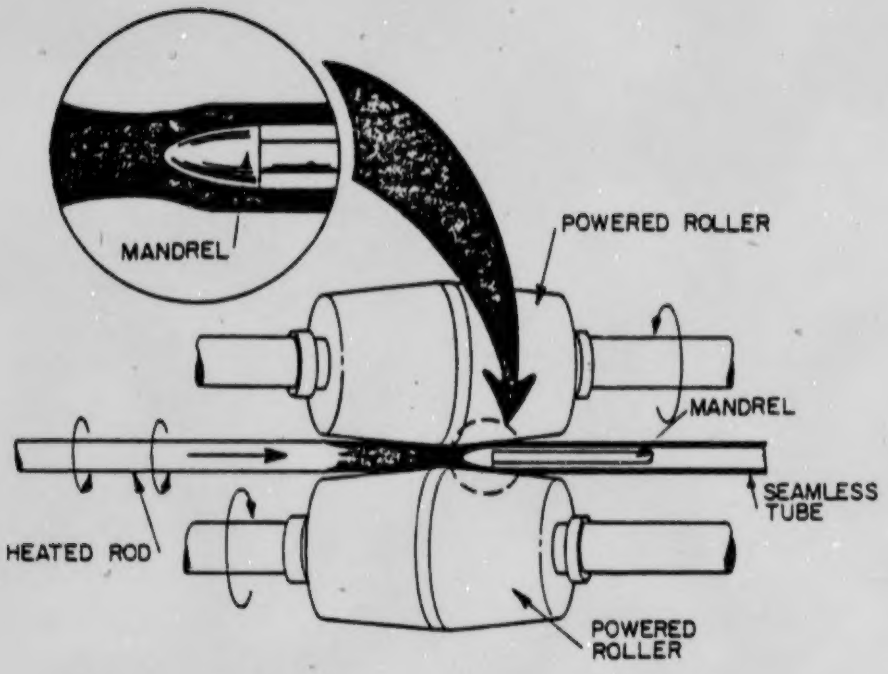

MANDREL
POWERED ROLLER
MANDREL
SEAMLESS TUBE
HEATED ROD
POWERED ROLLER

Figure 15-1-21. Seamless tubing production.

It can be produced in shapes other than round.

It can be produced in small runs (not economically feasible for hot finishes).

It can be produced with increased mechanical properties.

Cold-rolled tubing can be produced in all tube sizes from a hypodermic needle up to approximately 12" OD.

LARGE FORGINGS

Industry uses a considerable amount of steel forgings for items such as valve bodies, pressure vessels, heat exchanger parts and other high-strength applications including single forging weights up to 750,000 pounds. These open-die forgings are produced by hot working steel between the upper and lower dies of a hydraulic forging press, often with a capacity as high as 12,000 to 15,000 tons.

Forgings, after they have been hot worked, must be cooled under controlled conditions to prevent uneven cooling and subsequent internal metal rupture and metal flaking. This cooling is generally carried out in a large horizontal or vertical heat-treating furnace reversed into a cooling cycle. For some metallurgical properties, forgings may be quenched by using high-pressure water or oil.

EXERCISES

None.

MATERIALS

Piece of coded mild steel.
Cast iron.
Heat-treated tool steel and stainless steel.
Hydraulic piping.
Electrical conduit.

Wrought iron.
Vise.
File.
Drill.
Grinder.

PROCEDURES

1. To demonstrate differences between several types of steels and their methods of production, use a piece of each metal (mild steel, cast iron, heat-treated tool steel, stainless steel coded by number); file, drill, grind and machine each metal; observe differences and discuss them in class.
2. Use pieces of pipe; file, drill, grind and machine them; observe working properties and discuss them in class. (Use hydraulic pipe, electrical conduit, steel pipe, cast-iron pipe; student should collapse each pipe in a vise, file its outside surfaces, and drill a hole in it.)
3. Any material that is broken in 1 and 2 above or shows a broken end should be observed for type of fracture, and discussed in class.

DATA TABLE

None.

REFERENCE MATERIALS

Babcock and Wilcox Company. Steam: Its Generation and Use. New York: Babcock and Wilcox, 1975.

Bethlehem Steel Company. Modern Steels and Their Properties, Handbook No. 268-8. Bethlehem, PA: Bethlehem Steel Co.

Kent, R.T. Mechanical Engineers Handbook. 12th ed. New York: John Wiley & Sons, 1970.

TEST

Read each question carefully to be sure that you give the type of response each question requires. Your answers should be brief.

1. List the four main ingredients used in a blast furnace. State the purpose or function of each of the main ingredients.

   a.

   b.

   c.

   d.

2. What is the essential difference between steel and pig iron?

3. Name three major processes for making steel.

   a.

   b.

   c.

4. Common elements found in commercial steel are: carbon, manganese, silicon sulphur, phosphorus, and oxygen. List one metallurgical effect each of these elements has on the steel.

   a. Carbon

   b. Manganese

   c. Silicon

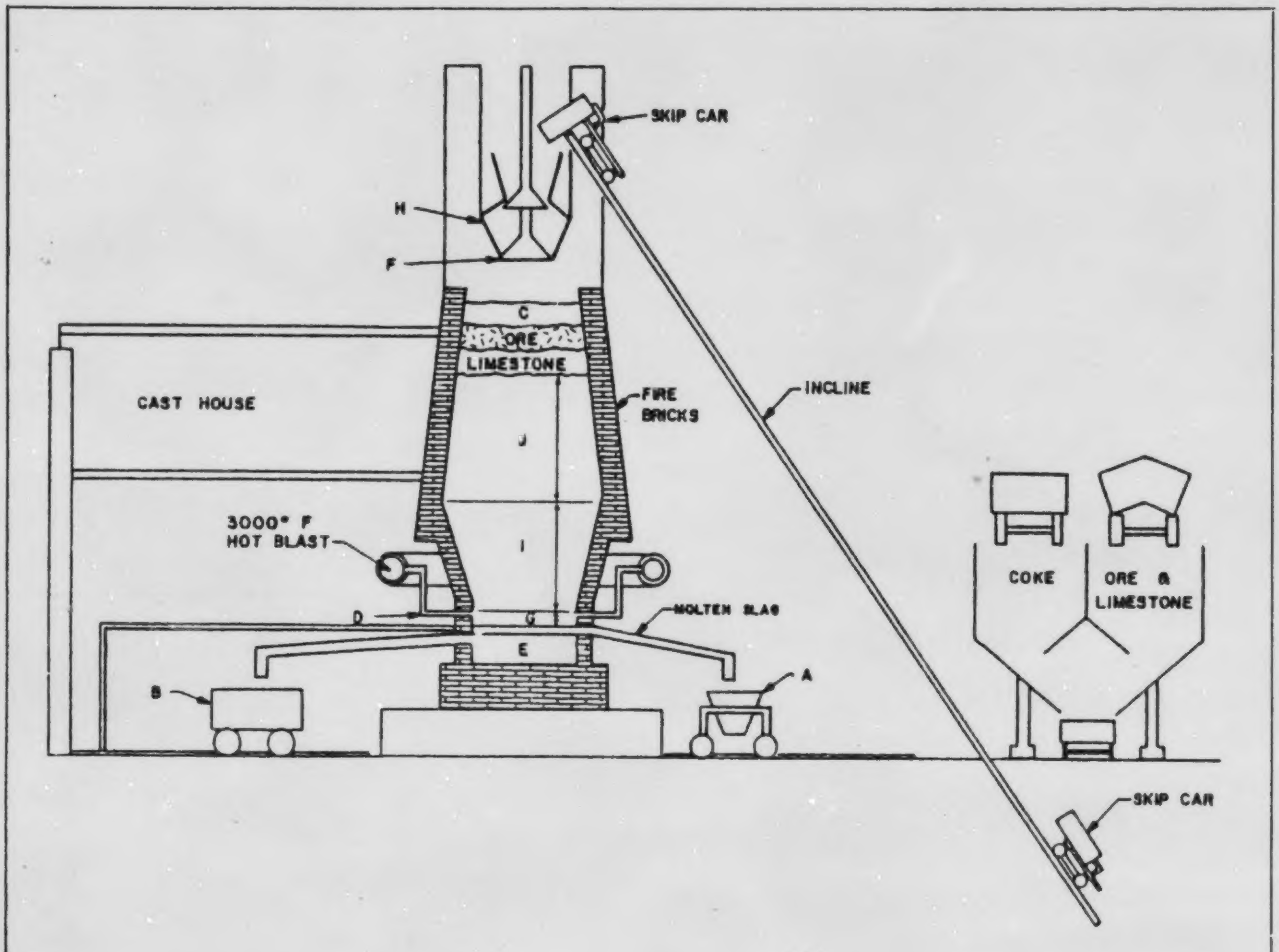
d. Sulphur ______________________________

e. Phosphorus ______________________________

f. Oxygen ______________________________

5. Identify the major parts of the blast furnace by matching the letter of the parts shown with the name of the part.
EXAMPLE: __A__ Slag Car

1. _____ Hearth
2. _____ Tuyere
3. _____ Hot Iron Car
4. _____ Top Hopper
5. _____ Bosh
6. _____ Bell
7. _____ Conestack
8. _____ Molten Iron
9. _____ Coke


SKIP CAR
H
F
C
ORE
LIMESTONE
CAST HOUSE
FIRE BRICKS
INCLINE
J
3000° F HOT BLAST
I
D
G
MOLTEN SLAG
E
B
A
COKE
ORE & LIMESTONE
SKIP CAR

6. What does the term "killed" steel mean?

7. What does the term "rimmed" steel mean? For what uses are rimmed steels particularly suitable?

8. What is alloy steel?

9. What are two reasons alloy steels are more difficult and expensive to produce than carbon steels?

a. ____________________

b. ____________________

10. List three of the most commonly used alloying elements. Give one effect that each element imparts or helps produce in the finished steel.

a. ____________________

b. ____________________

c. ____________________

11. Why does hot rolling improve the material strength of steel?

12. What name is given to the permanent shaping of steel at temperatures and rates of straining, such that strain hardening is prevented or does not occur?

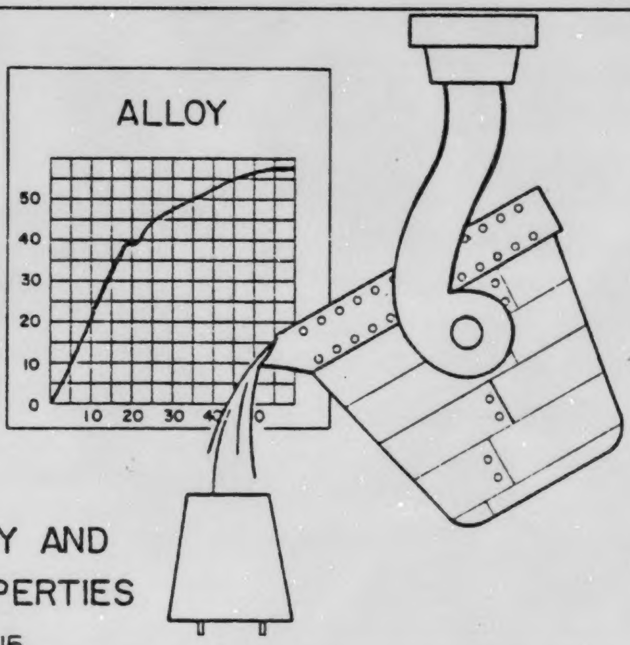
13. What does the term "forging" mean in the steel industry?

14. What does the term "cold extrusion" mean?

15. Name one advantage of cold-finished seamless tubing over hot-finished seamless tubing.

NUCLEAR TECHNOLOGY

MODULE 15-2 CHEMICAL ANALYSIS OF METALS


ALLOY
50
40
30
20
10
0
10
20
30

METALLURGY AND
METALS PROPERTIES
COURSE 15

COURSE MODULES

COURSE 15 METALLURGY AND METALS PROPERTIES

	MODULE 15-1	Fabrication Processes for Metals
⇨	MODULE 15-2	Chemical Analysis of Metals
	MODULE 15-3	Basic Metallurgical Concepts
	MODULE 15-4	Properties of Steel
	MODULE 15-5	Metallographic Examination
	MODULE 15-6	Mechanical Testing - Tensile, Bend, Hardness
	MODULE 15-7	Mechanical Testing - Impact, Nick Break, Fatigue
	MODULE 15-8	Failure Mechanisms in Metals

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Technical Education Research Center
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4201 Lake Shore Drive, Suite 111
Waco, Texas 76710

INTRODUCTION

Materials used in nuclear power plants must comply with customer order specifications and usually with American Society of Mechanical Engineers (ASME), American Iron and Steel Institute (AISI), American Society for Testing and Materials (ASTM) and American National Standards Institute (ANSI) requirements. The amounts of impurities and alloying elements in these materials (especially the ferrous metals) are extremely important and, thus, tightly controlled.

Actual amounts of impurities and alloying elements are verified by independent testing laboratories and compared to limits in codes and specifications. Although the student will not have to actually make these complex chemical analyses, the student should be familiar with basic procedures. Most important is sufficient familiarity with code requirements to tell if a particular chemical composition is acceptable.

This module is concerned mainly with ferrous metals used in primary containment systems that must meet ASME Boiler and Pressure Vessel Code requirements.

MODULE PREREQUISITES

The student must have successfully completed a course in chemistry.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Discuss how the percentage of alloying elements in steel is determined and state where accepted standard test procedures are found.
2. Describe procedures for determining acceptable percentages of alloying elements in steel, given appropriate maximum and minimum tables.
3. Describe an emission spectroscopy unit, including its calibration and alignment requirements and procedures.
4. Determine percentage of carbon in a steel sample by using the combustion gravimetric method.
5. Describe operation of a carbon analyzer; use an analyzer to determine the percentage of carbon in a steel sample.
6. Recognize that specific samples are required for each heat.
7. Differentiate between a typical analysis and an actual analysis.
8. Explain the difference between chemical and physical analyses.

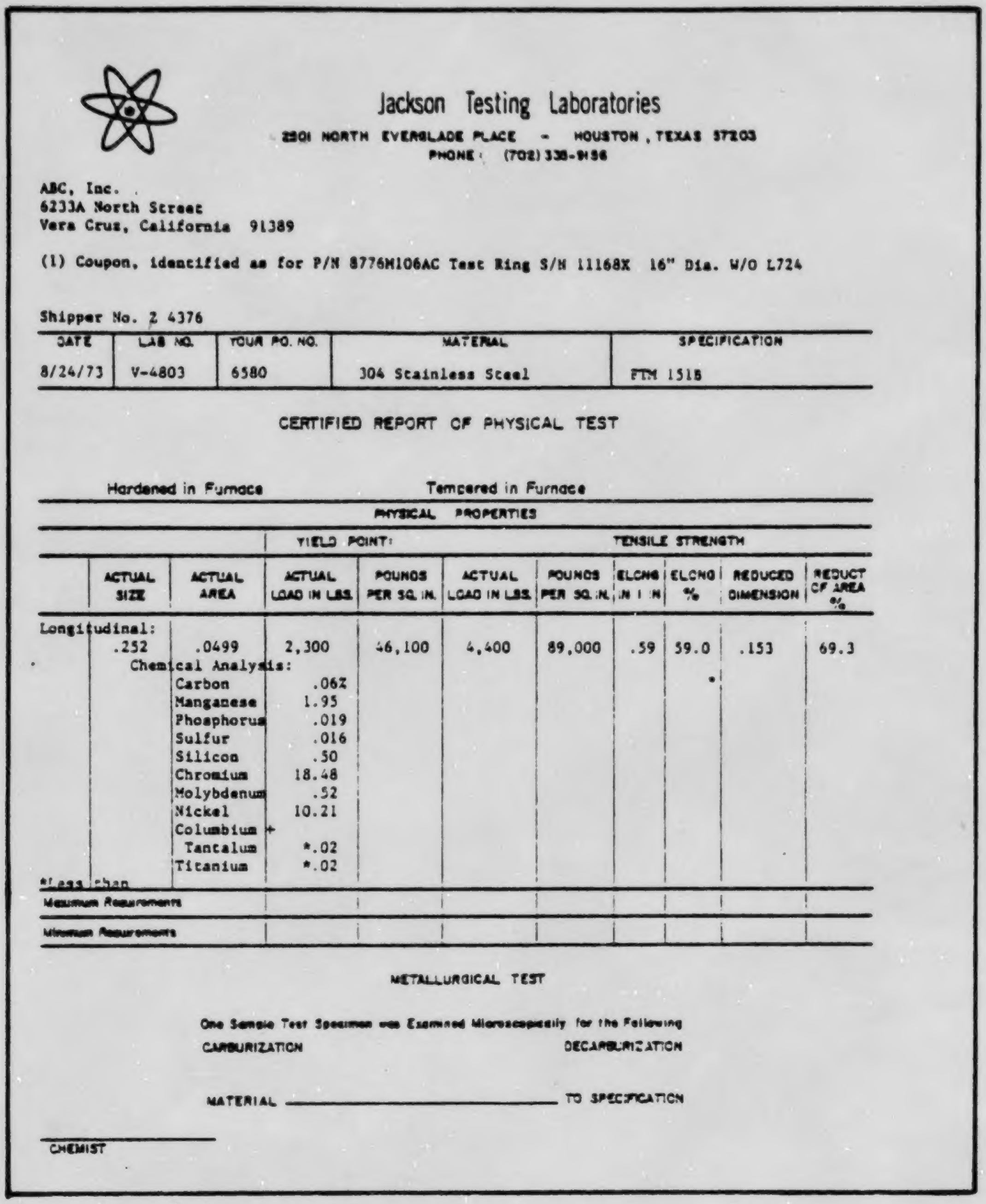
OVERVIEW

Metals usually contain certain amounts of impurities and alloying elements. The impurities may have been present in the original raw material, or they may have been added to alter mechanical properties. In either case, percentages of these elements must be known to enable a determination of the material's ability to perform satisfactorily in service, according to codes and specifications. Such percentages are determined by an independent laboratory (by trained chemical and metallurgical technicians). Most tests are complex, requiring sophisticated equipment. This module gives, in very general terms, an overview of the chemical analyses of metals.

ASME REQUIREMENTS

The ASME Boiler and Pressure Vessel Code states that most materials used in Code-related components shall be certified by a Certified Material Test Report. The code is referring specifically to those materials which provide a pressure retaining function, that is to say, those materials used at a pressure boundary. This report includes the actual results of all required chemical analyses, tests, examinations, repairs and heat treatments performed on the material (Figure 15-2-1). The tests are performed by independent laboratories because 1) the intent is for them to be unbiased and 2) they are assumed to have the necessary expertise and equipment.

Material specifications for ferrous metals are presented in Section II, Part A, of the ASME Code. The Code states that a chemical analysis shall be made by the manufacturer



Jackson Testing Laboratories

2501 NORTH EVERGLADE PLACE - HOUSTON, TEXAS 37203
PHONE: (702) 338-9156

ABC, Inc.
6233A North Street
Vera Cruz, California 91389

(1) Coupon, identified as for P/N 8776M106AC Test Ring S/N 11168X 16" Dia. W/O L724

Shipper No. Z 4376

DATE	LAB NO.	YOUR PO. NO.	MATERIAL	SPECIFICATION
8/24/73	V-4803	6580	304 Stainless Steel	FTM 151B

CERTIFIED REPORT OF PHYSICAL TEST

Hardened in Furnace Tempered in Furnace

PHYSICAL PROPERTIES

			YIELD POINT:		TENSILE STRENGTH					
	ACTUAL SIZE	ACTUAL AREA	ACTUAL LOAD IN LBS.	POUNDS PER SQ. IN.	ACTUAL LOAD IN LBS.	POUNDS PER SQ. IN.	ELONG IN 1 IN	ELONG %	REDUCED DIMENSION	REDUCT OF AREA %
Longitudinal:										
	.252	.0499	2,300	46,100	4,400	89,000	.59	59.0	.153	69.3
	Chemical Analysis:									
		Carbon	.06%							
		Manganese	1.95							
		Phosphorus	.019							
		Sulfur	.016							
		Silicon	.50							
		Chromium	18.48							
		Molybdenum	.52							
		Nickel	10.21							
		Columbium + Tantalum	*.02							
		Titanium	*.02							
*Less than										
Maximum Requirements										
Minimum Requirements										

METALLURGICAL TEST

One Sample Test Specimen was Examined Microscopically for the Following

CARBURIZATION DECARBURIZATION

MATERIAL ______________________ TO SPECIFICATION

CHEMIST

Figure 15-2-1. A typical certified materials test report (from an independent testing laboratory).

to determine the percentage of each element specified in the individual material specification. This analysis shall be made from a test specimen, preferably taken during the pouring process. The chemical composition thus determined shall be reported to the purchaser (or a representative) and, to be accepted, must conform to the chemical analysis requirements of the applicable specification.

The Code further states that the following ASTM standards shall be used:

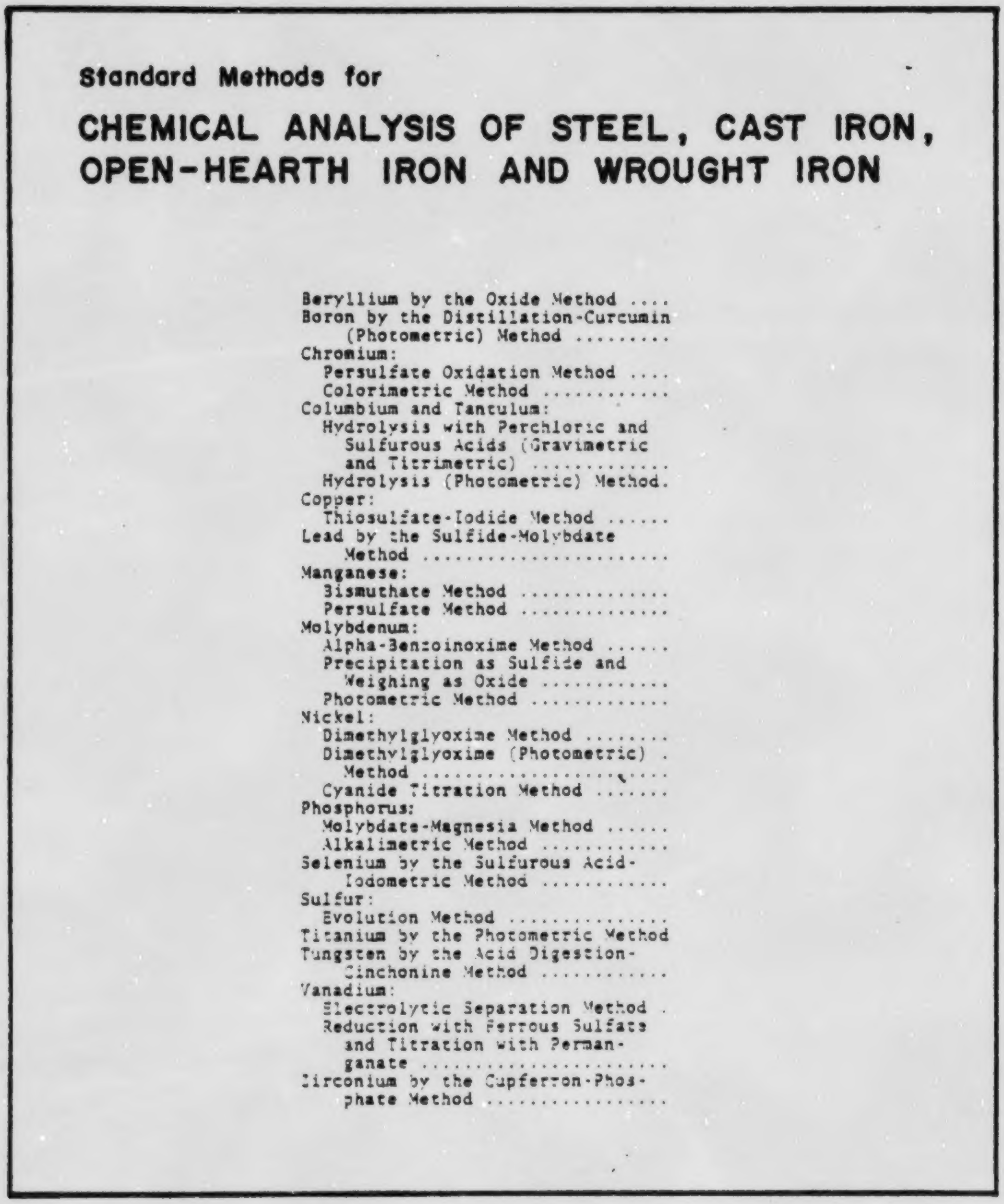
E30 - Chemical Analysis of Steel, Cast Iron, Open Hearth Iron and Wrought Iron.

E350- Chemical Analysis of Carbon Steel, Low-Alloy Steel, Silicon Electrical Steel, Ingot Iron and Wrought Iron.

These standards, as discussed in the next section, provide an acceptable procedure for the chemical analyses of the given ferrous materials.

ASTM STANDARDS

These standards provide the analytical procedures for determining percentages of various elements. The apparatus and reagents required for each determination are listed in separate sections preceding the procedure; for example, one list gives the various analytical procedures (Figure 15-2-2) for Standard E30 and another (Figure 15-2-3) for Standard E350. The student is referred to the particular standards for details. Some of the tests are briefly described below.

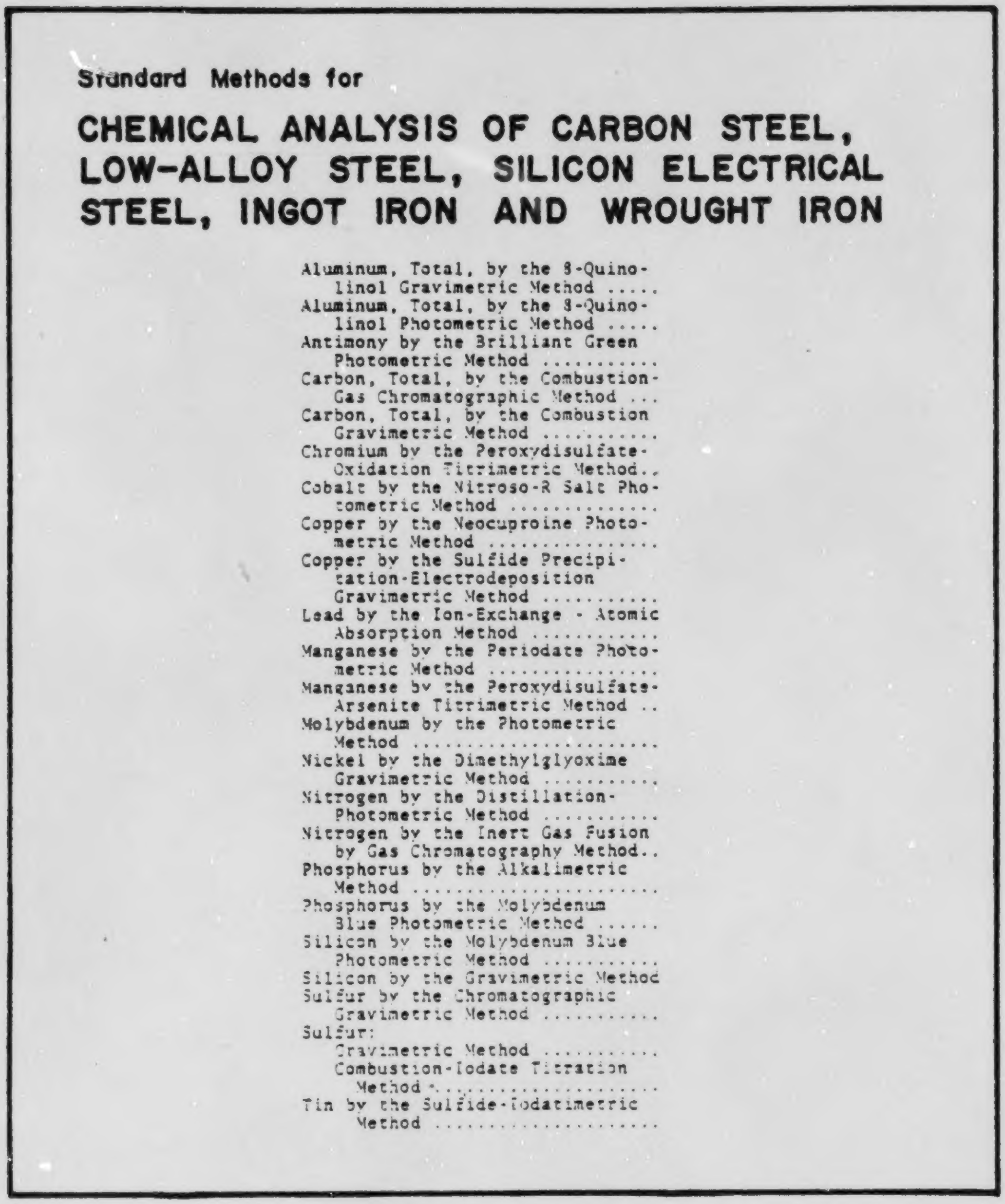


Standard Methods for

CHEMICAL ANALYSIS OF STEEL, CAST IRON, OPEN-HEARTH IRON AND WROUGHT IRON

Beryllium by the Oxide Method ....
Boron by the Distillation-Curcumin (Photometric) Method ....
Chromium:
  Persulfate Oxidation Method ....
  Colorimetric Method ....
Columbium and Tantalum:
  Hydrolysis with Perchloric and Sulfurous Acids (Gravimetric and Titrimetric) ....
  Hydrolysis (Photometric) Method.
Copper:
  Thiosulfate-Iodide Method ......
Lead by the Sulfide-Molybdate Method ....
Manganese:
  Bismuthate Method ....
  Persulfate Method ....
Molybdenum:
  Alpha-Benzoinoxime Method ......
  Precipitation as Sulfide and Weighing as Oxide ....
  Photometric Method ....
Nickel:
  Dimethylglyoxime Method ....
  Dimethylglyoxime (Photometric) . Method ....
  Cyanide Titration Method ....
Phosphorus:
  Molybdate-Magnesia Method ......
  Alkalimetric Method ....
Selenium by the Sulfurous Acid-Iodometric Method ....
Sulfur:
  Evolution Method ....
Titanium by the Photometric Method
Tungsten by the Acid Digestion-Cinchonine Method ....
Vanadium:
  Electrolytic Separation Method .
  Reduction with Ferrous Sulfate and Titration with Permanganate ....
Zirconium by the Cupferron-Phosphate Method ....

Figure 15-2-2. Analytical procedures for ASTM Standard E30. (1976 Annual Book of ASTM Standards, Part 12, Chemical Analysis of Metals; Sampling and Analysis of Metal-Bearing Ores.)



Standard Methods for

CHEMICAL ANALYSIS OF CARBON STEEL, LOW-ALLOY STEEL, SILICON ELECTRICAL STEEL, INGOT IRON AND WROUGHT IRON

Aluminum, Total, by the 8-Quinolinol Gravimetric Method .....
Aluminum, Total, by the 8-Quinolinol Photometric Method .....
Antimony by the Brilliant Green Photometric Method ....
Carbon, Total, by the Combustion-Gas Chromatographic Method ...
Carbon, Total, by the Combustion Gravimetric Method ....
Chromium by the Peroxydisulfate-Oxidation Titrimetric Method..
Cobalt by the Nitroso-R Salt Photometric Method ....
Copper by the Neocuproine Photometric Method ....
Copper by the Sulfide Precipitation-Electrodeposition Gravimetric Method ....
Lead by the Ion-Exchange - Atomic Absorption Method ....
Manganese by the Periodate Photometric Method ....
Manganese by the Peroxydisulfate-Arsenite Titrimetric Method ..
Molybdenum by the Photometric Method ....
Nickel by the Dimethylglyoxime Gravimetric Method ....
Nitrogen by the Distillation-Photometric Method ....
Nitrogen by the Inert Gas Fusion by Gas Chromatography Method..
Phosphorus by the Alkalimetric Method ....
Phosphorus by the Molybdenum Blue Photometric Method ......
Silicon by the Molybdenum Blue Photometric Method ....
Silicon by the Gravimetric Method
Sulfur by the Chromatographic Gravimetric Method ....
Sulfur:
    Gravimetric Method ....
    Combustion-Iodate Titration Method ....
Tin by the Sulfide-Iodatimetric Method ....

Figure 15-2-3. Analytical procedures for ASTM Standard E350. (1976 Annual Book of ASTM Standards, Part 12, Chemical Analysis of Metals; Sampling and Analysis of Metal-Bearing Ores.)

EFFECTS OF CHEMICAL ELEMENTS

The effects of the commonly specified chemical elements in steel was discussed in Module 15-1. In practice it has been found that the effect of any particular element will often depend upon the quantities of other elements also present in the steel. For example, the total effect of a combination of alloying elements on the hardenability of a particular type of steel is usually greater than the sum of their individual contributions. This type of interrelation should be taken into account whenever a change in a specified analysis is evaluated.

In module 15-1 for example, the effects of carbon were discussed. Carbon is the principal hardening element in steel, with each additional increment of carbon increasing the hardness and tensile strength of the steel. As a result, a carbon analysis is performed on each batch of steel produced to determine the actual carbon content. Similar analyses are also performed to determine the actual content of each of the other chemical elements found in steel.

The following discussion considers the various techniques used in determining the carbon content of a steel sample.

CARBON ANALYSIS

A combustion gravimetric method of analysis determines carbon content in concentrations from 0.05 to 1.80 percent in carbon steels and low-alloy steels. A sample is burned in a stream of oxygen and the carbon dioxide in the evolved gases is collected in a suitable absorbent, and weighed. Oxygen flow rates and sweep times, as well as control of plate current for induction heating, depend upon the equipment used and the type of sample analyzed. In any event, control of these parameters is established by simultaneous analysis of control samples with carbon content and alloy characteristics similar to those of the sample to be analyzed. This method of analysis for elements is very time consuming.

The combustion-gas chromatographic method, however, is physical (rather than chemical) and takes less than two minutes. This technique involves a method of separating and analyzing mixtures of the combustion gas in an ascending molecular-weight sequence onto a solid adsorbent material. A conventional combustion principle is employed, but special sampling techniques make it necessary for carefully weighing the sample to be analyzed. Also various electrical methods are used to measure the carbon (or sulphur) dioxide evolved.

There are several other techniques also used for carbon analysis. These include:

- Infrared absorption - This technique involves the measurement of infrared radiation (light waves or electromagnetic waves whose wavelength lies in the range from 0.75 micrometers to 1000 micrometers) emitted from a sample that has been subjected to arc or spark excitation.
- measurement of the thermal conductivity of a steel sample also yields a measure of its carbon content. One such instrument, which uses the thermal conductivity principle with the combustion of the sample in a high frequency furnace is the Leco 50 second carbon analyzer.
- change in the conductivity of an electrolyte containing the sample enables one to obtain a measure of its carbon content.

In another specific method, carbon is converted to carbon dioxide by combustion in a stream of oxygen. The carbon dioxide is absorbed onto a suitable grade of Zeolite (a porous aluminum, calcium or sodium silicate compound), then released by heating the Zeolite, and swept by helium or oxygen into a chromatographic column. The amount of carbon dioxide is then measured in a thermistor-type conductivity cell. A cell of this type measures the change in heat transfer due to the presence of the carbon dioxide. This technique is a quick technique for measuring carbon content, but not an extremely accurate one. This method, used by commercial analyzers equipped to carry out the operation automatically, is calibrated by using steels with known carbon contents.

EMISSION SPECTROSCOPY

The fluorescent emission of x-rays provides one of the most potent tools available to the analyst for the study of metals. Excitation of a sample is achieved by irradiation with a beam of primary x-rays. In this process, the primary x-ray beam strikes the specimen and subsequently x-rays of a longer wavelength are emitted within a fraction of a second (typically less than 10^{-8} second).

Each heavy element in the sample is excited to emit a different frequency, which it would if it were made the target in a separate x-ray tube. Thus, there are characteristic wavelengths of x-rays emitted by each element in the specimen shown in Figure 15-2-4. These wavelengths can then be measured using a diffraction apparatus, operated with a crystal grating of known spacing, is called an x-ray spectrometer (Figure 15-2-4).

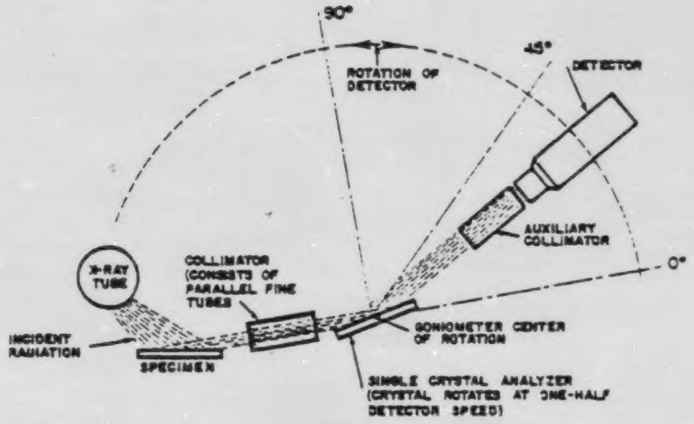
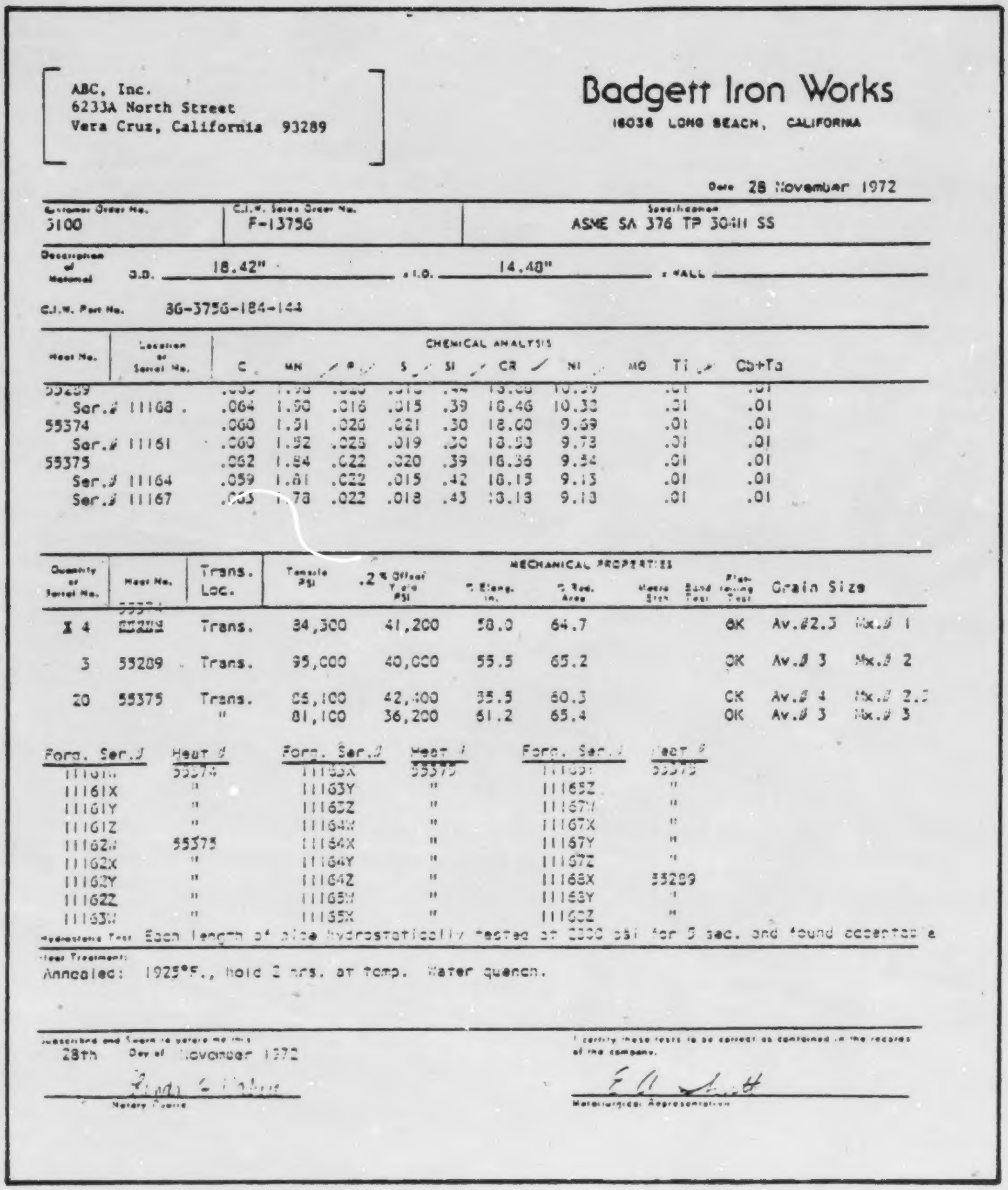

90°
ROTATION OF DETECTOR
45°
DETECTOR
AUXILIARY COLLIMATOR
0°
X-RAY TUBE
COLLIMATOR (CONSISTS OF PARALLEL FINE TUBES
GONIOMETER CENTER OF ROTATION
INCIDENT RADIATION
SPECIMEN
SINGLE CRYSTAL ANALYZER (CRYSTAL ROTATES AT ONE-HALF DETECTOR SPEED)

Figure 15-2-4. Basic geometry of an x-ray emission spectrometer.

X-ray emission provides a convenient means of analysis for high-alloy steels and for heat-resistant alloys of the chromium-nickel-cobalt type. Analyses of low percentages are limited by the relationship between background radiation and the radiant power of desired elements.

INDUSTRIAL APPLICATION

A Certified Materials Test Report for a typical purchase order (Figure 15-2-5) must be accompanied by an independent chemical analysis on the same material (Figure 15-2-1). All of these results are then compared with chemical composition limits from the ASME Code (Figure 15-2-6). Note that, in the example, all actual percentages are within acceptable limits.



ABC, Inc.
6233A North Street
Vera Cruz, California 93289

Badgett Iron Works
16036 LONG BEACH, CALIFORNIA

Date 28 November 1972

Customer Order No.	C.I.W. Sales Order No.	Specification
3100	F-13756	ASME SA 376 TP 304H SS

Description of Material O.D. 18.42" x I.D. 14.40" x WALL

C.I.W. Part No. 36-3756-184-144

Heat No.	Location or Serial No.	C	MN	P	S	SI	CR	NI	MO	Ti	Cb+Ta
55289		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		.01	.01
	Ser.# 11168	.064	1.90	.016	.015	.39	18.46	10.32		.01	.01
55374		.060	1.51	.026	.021	.30	18.60	9.69		.01	.01
	Ser.# 11161	.060	1.52	.025	.019	.30	18.53	9.73		.01	.01
55375		.062	1.84	.022	.020	.39	18.36	9.54		.01	.01
	Ser.# 11164	.059	1.81	.022	.015	.42	18.15	9.13		.01	.01
	Ser.# 11167	.063	1.78	.022	.018	.43	18.13	9.13		.01	.01

MECHANICAL PROPERTIES

Quantity or Serial No.	Heat No.	Trans. Loc.	Tensile PSI	.2 % Offset Yield PSI	% Elong. in.	% Red. Area	Macro Etch	Bend Test	Flattening Test	Grain Size	
4	55374 ~~[illegible]~~	Trans.	84,300	41,200	58.0	64.7			OK	Av.#2.5	Mx.# 1
3	55289	Trans.	85,000	40,000	55.5	65.2			OK	Av.# 3	Mx.# 2
20	55375	Trans.	85,100	42,400	55.5	60.3			OK	Av.# 4	Mx.# 2.5
		"	81,100	36,200	61.2	65.4			OK	Av.# 3	Mx.# 3

Forg. Ser.#	Heat #	Forg. Ser.#	Heat #	Forg. Ser.#	Heat #
11161W	55374	11163X	55375	[illegible]	55375
11161X	"	11163Y	"	11165Z	"
11161Y	"	11163Z	"	11167W	"
11161Z	"	11164W	"	11167X	"
11162W	55375	11164X	"	11167Y	"
11162X	"	11164Y	"	11167Z	"
11162Y	"	11164Z	"	11168X	55289
11162Z	"	11165W	"	11168Y	"
11163W	"	11165X	"	11168Z	"

Hydrostatic Test: Each length of pipe hydrostatically tested at 2300 psi for 5 sec. and found acceptable

Heat Treatment:
Annealed: 1925°F., hold 2 hrs. at temp. Water quench.

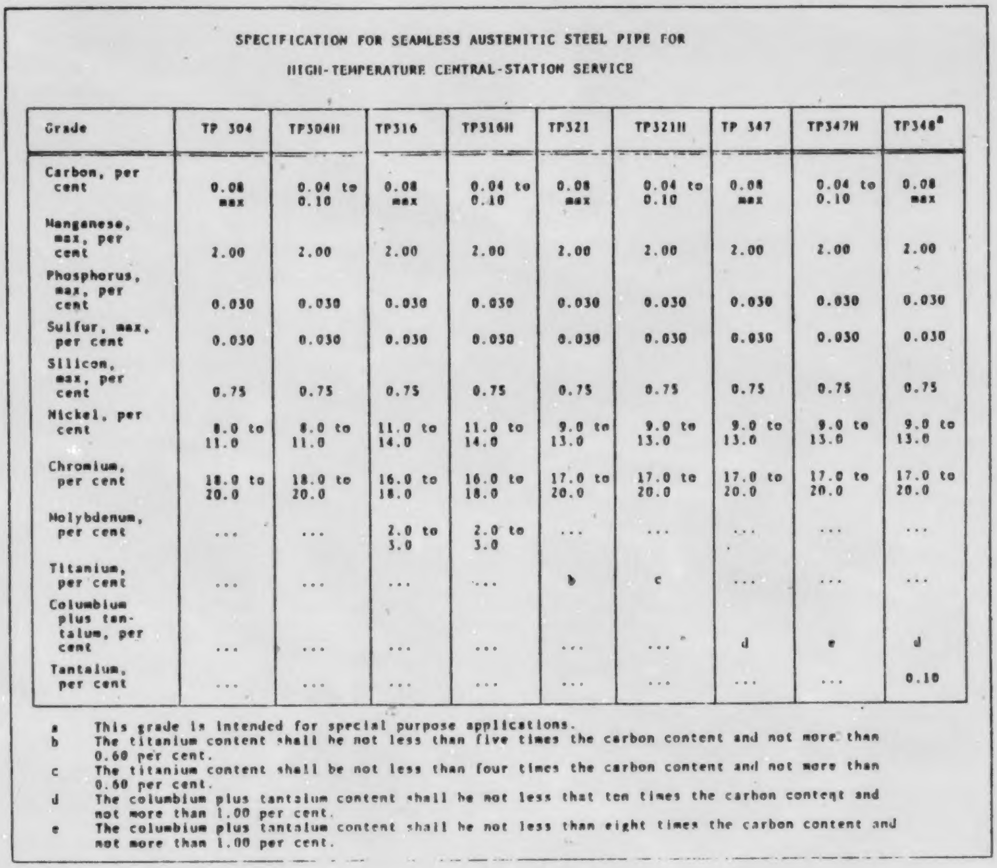
Subscribed and Sworn to before me this
28th Day of November 1972

Notary Public

I certify these tests to be correct as contained in the records of the company.

E. A. Smith
Metallurgical Representative

Figure 15-2-5. Typical certified materials test report (from manufacturer).



SPECIFICATION FOR SEAMLESS AUSTENITIC STEEL PIPE FOR
HIGH-TEMPERATURE CENTRAL-STATION SERVICE

Grade	TP 304	TP304H	TP316	TP316H	TP321	TP321H	TP 347	TP347H	TP348[a]
Carbon, per cent	0.08 max	0.04 to 0.10	0.08 max	0.04 to 0.10	0.08 max	0.04 to 0.10	0.08 max	0.04 to 0.10	0.08 max
Manganese, max, per cent	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Phosphorus, max, per cent	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
Sulfur, max, per cent	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
Silicon, max, per cent	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Nickel, per cent	8.0 to 11.0	8.0 to 11.0	11.0 to 14.0	11.0 to 14.0	9.0 to 13.0	9.0 to 13.0	9.0 to 13.0	9.0 to 13.0	9.0 to 13.0
Chromium, per cent	18.0 to 20.0	18.0 to 20.0	16.0 to 18.0	16.0 to 18.0	17.0 to 20.0	17.0 to 20.0	17.0 to 20.0	17.0 to 20.0	17.0 to 20.0
Molybdenum, per cent	...	...	2.0 to 3.0	2.0 to 3.0	...	...	...	...	...
Titanium, per cent	...	...	...	...	b	c	...	...	...
Columbium plus tantalum, per cent	...	...	...	...	...	...	d	e	d
Tantalum, per cent	...	...	...	...	...	...	...	...	0.10

a This grade is intended for special purpose applications.
b The titanium content shall be not less than five times the carbon content and not more than 0.60 per cent.
c The titanium content shall be not less than four times the carbon content and not more than 0.60 per cent.
d The columbium plus tantalum content shall be not less that ten times the carbon content and not more than 1.00 per cent.
e The columbium plus tantalum content shall be not less than eight times the carbon content and not more than 1.00 per cent.

Figure 15-2-6. Chemical composition limits (ASME Code).

For nuclear power plant applications, Title 10 of the Code of Federal Regulations, Part 50 specifies which codes, either ASME or ASTM apply for particular power plant components.

EXERCISES

1. Discuss how the percentages of alloying elements in steel are determined; state where accepted standard test procedures are found.
2. Give the chemical composition test results (to be noted in the appropriate spaces on next pages) and determine from the ASME Code which (if any) of the percentages are out of limits.

Type: Electric-Resistance-Welded Steel Pipe, SA-134,
Grade A.

Element	Percentage, Actual	Percentage, Max.
Carbon	0.21	
Manganese	0.87	
Sulphur	0.050	
Phosphorus	0.50	
Comments:		

Type: Seamless Carbon Steel Pipe for Process Piping, SA-524, Grade II.

Element	Percentage, Actual	Percentage, Max. (and Min.)
Carbon	0.20	
Manganese	1.00	
Phosphorus	0.058	
Sulphur	0.048	
Silican	0.20	
Comments:		

MATERIALS

Carbon steel sample.

Iron (low carbon) accelerator, iron chips.

Acetone.

Oxygen supply.

Tin (low carbon) accelerator, granular.

Tin-coated copper accelerator, granular.

Copper and tin metals in the ratio of approximately 30:1.

Induction furnace.

Flow meter.

Sulfuric acid bubbler tube.

Analytical balance.
Oxygen purifier.
Catalyst heater.
Particle filter.
Carbon dioxide purifier.
Stopcocks.
Leco 50-second carbon analyzer.

PROCEDURES

OPERATION OF AN EMISSION SPECTROSCOPY UNIT

1. Visit an independent materials testing laboratory and examine an emission spectroscopy unit.
2. Describe operation of the unit:

    Calibration.
    Alignment.
    Analysis.
    Working and calibration curves.

DETERMINATION OF CARBON PERCENTAGE IN A STEEL SAMPLE BY COMBUSTION GRAVIMETRIC METHOD

Use the method discussed in this module; determine percentage of carbon in a steel sample. (Refer to ASTM Standard E350 for procedural details.)

OPERATION OF A CARBON ANALYZER

Use a carbon analyzer to determine the percentage of carbon in a steel sample. (Refer to manufacturer of carbon analyzer for operating procedures and safety requirements.)

DATA TABLE

None.

REFERENCE MATERIALS

Americal Society of Mechanical Engineers (ASME). ASME Boiler and Pressure Vessel Code. New York: ASME, 1974.

American Society for Testing and Materials (ASTM). Annual Book of ASTM Standards, Part 12. Philadelphia: ASTM.
See especially ASTM designations E173 and E350-E354 and ASTM standards E29, E50, E59 and E60.

Bergeman, Myron L. Manufacturing Processes. New York: John Wiley & Sons, 1969.

TEST

Read each question carefully. Be sure your responses gives the specific information each question requires. Your answers should be brief.

1. What is the purpose of the standards prepared by the American Society for Testing and Materials (ASTM)?

2. Name two groups or professional organizations besides ASTM, that set requirements and/or standards for materials that are used in the nuclear power plants.

   a. ______________________

   b. ______________________

3. What information is included in a Certified Material Test Report?

4. Why are tests on materials done by independent laboratories?

5. What is the purpose of the chemical analyses that the Boiler and Pressure Vessel Code requires the manufacturer of ferrous metals to perform?

6. What is the purpose of the combustion gravimetric method of analysis?

____

7. Briefly describe the combustion gravimetric method.

____

____

____

8. What is the purpose of the combustion-gas chromatographic method of analysis?

____

____

____

9. What is the purpose of X-ray emission spectroscopy?

____

10. Briefly describe the emission spectroscopy method of analysis.

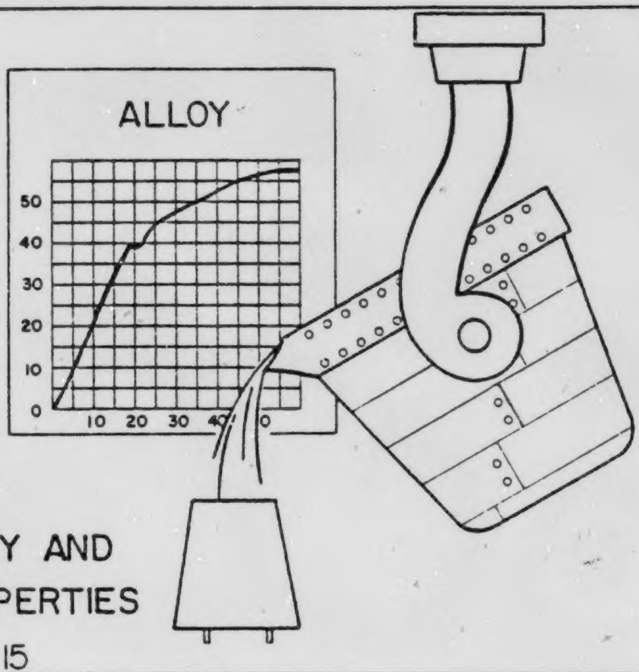
____

____

____

NUCLEAR TECHNOLOGY

MODULE 15-3 BASIC METALLURGICAL CONCEPTS.


ALLOY
50
40
30
20
10
0
10
20
30
40
0

METALLURGY AND
METALS PROPERTIES
COURSE 15

COURSE MODULES

COURSE 15 METALLURGY AND METALS PROPERTIES

	MODULE 15-1	Fabrication Processes for Metals
	MODULE 15-2	Chemical Analysis of Metals
⇨	MODULE 15-3	Basic Metallurgical Concepts
	MODULE 15-4	Properties of Steel
	MODULE 15-5	Metallographic Examination
	MODULE 15-6	Mechanical Testing - Tensile, Bend, Hardness
	MODULE 15-7	Mechanical Testing - Impact, Nick Break, Fatigue
	MODULE 15-8	Failure Mechanisms in Metals

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Technical Education Research Center
Southwest
4201 Lake Shore Drive, Suite 111
Waco, Texas 76710

INTRODUCTION

Most metals used in power plant equipment are alloys - materials containing two or more metallic elements. And many of these alloys were unknown only a decade or two ago. The space age, with its unique demands and extensive opportunities for materials research and development, literally ushered in a new era in metallurgy - the era of comprehensive alloys.

This module presents a simplified overview of the atomic processes involved in forming an alloy.

MODULE PREREQUISITES

Student should have successfully completed analytical chemistry, Module 15-1, "Fabrication Processes for Metals," and Module 15-2, "Chemical Analysis of Metals."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Describe the mechanisms of solidification of materials.
2. Demonstrate solid-liquid equilibrium with two component

alloys and explain results.

3. Explain lead-tin experimental data.

CRYSTALLINE STRUCTURE

Energy contained in matter consists of motion: motion of the atom as a whole, revolutions of electrons about their nuclei, and spin of the electrons on their own axes. Atoms may be altered by temperature changes, by pressure changes and by proximity to one another.

If temperature is not too high, atoms usually tend to group themselves into geometrical patterns reflecting minimum energy states.

Atoms grouped in an orderly geometric arrangement have the property of rigidity; work must be done on them to distort their pattern (lattice). This condition is termed the solid (crystalline) state. In the crystalline state, the atoms are arranged in a regular way. The arrangement of atoms in all crystalline solids falls into 14 categories as shown in Figure 15-3-1 and further explained in Table 15-3-1.

The crystalline arrangement identified in Figure 15-3-1 includes the metals and most minerals. Table 15-3-1 briefly explains the general nature of these crystalline structures.

Table 15-3-1

Crystalline Structure Arrangement shown in Figure 15-3-1

1. Cubic, or Regular. These axes of equal length which intersect at right angles.
2. Tetragonal. Three axes which intersect at right angles. Two horizontal axes of equal length, and vertical axis which is either longer or shorter than the horizontals.
3. Orthorhombic. Three axes of different lengths which intersect at right angles.
4. Monoclinic. Three axes of different lengths, two of which intersect at right angles, the third oblique to one of the others.
5. Triclinic or Anorthic. Three axes of unequal length and all oblique to one another. The angles between axes are less than 90°, and are unequal.
6. Hexagonal. Four axes: three equal coplanar axes at 60°, and one at right angles to them.
7. Rhombohedral or Trigonal. Three axes equally inclined, not at right angles; all unequal.

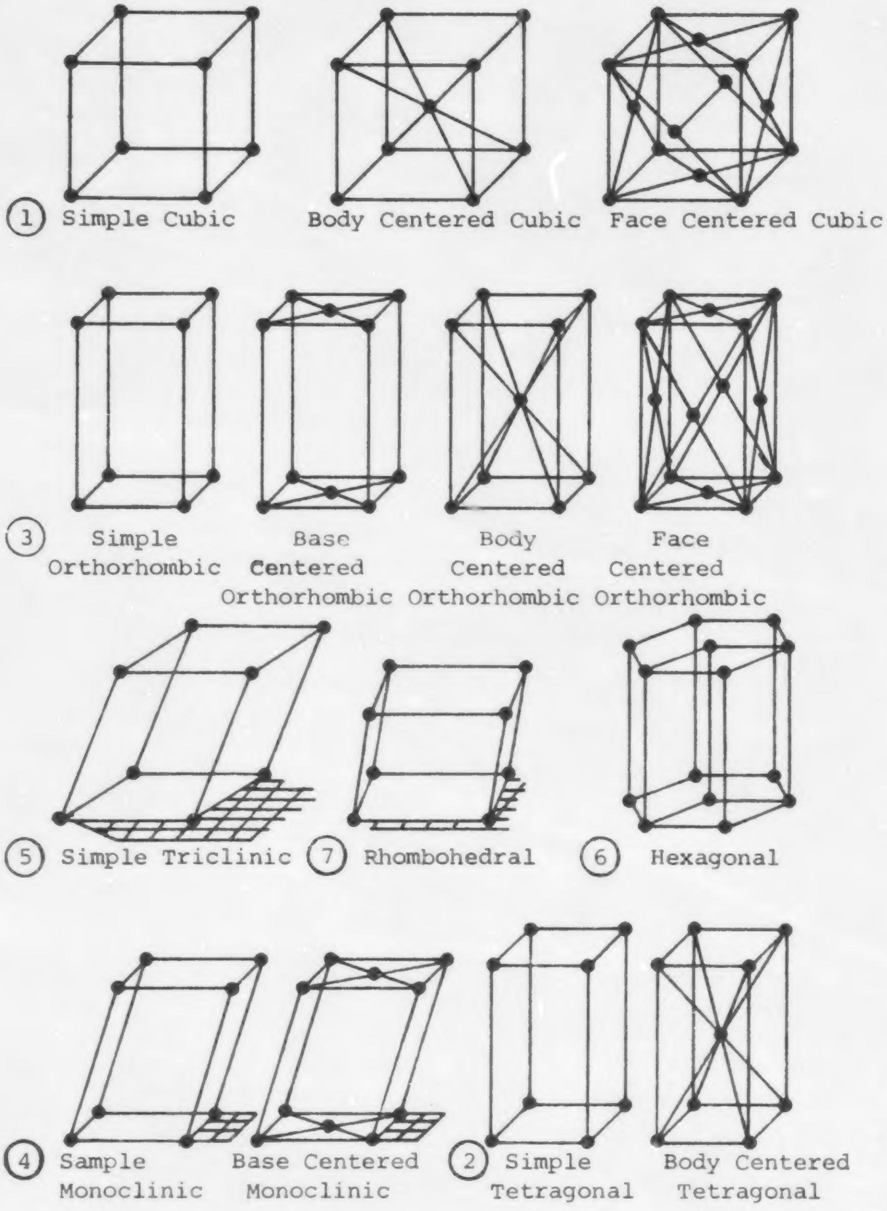

① Simple Cubic
Body Centered Cubic
Face Centered Cubic
③ Simple Orthorhombic
Base Centered Orthorhombic
Body Centered Orthorhombic
Face Centered Orthorhombic
⑤ Simple Triclinic
⑦ Rhombohedral
⑥ Hexagonal
④ Sample Monoclinic
Base Centered Monoclinic
② Simple Tetragonal
Body Centered Tetragonal

Figure 15-3-1 The Fourteen Crystalline Arrangements Possible for Solids

The number of ways in which an atom arrangement can be repeated to form a solid is limited to 14 by the geometries of space division. Any one of these arrangements, when repeated in space, forms the lattice structure characteristic of a crystalline material. It was discovered that corresponding angles between faces of different crystals of the same substances were always the same regardless of the size of the crystal. This inferred that all crystals of a particular substance must be comprised of similar small units which are duplicated over and over again in the growth of the crystal. As stated, a crystal is a rigid body in which the constituent particles are arranged in a repeating pattern. The forces of chemical bonding causes this repetition. It is the properties of this repeated pattern which control properties like strength, ductility, density, conductivity and shape. Close study of the angles and axis lengths made it clear that every crystalline substance has a structure built upon a space lattice characteristic of the substance. The same study showed that the lattice structures of all crystals are divided into the seven "basic" crystal systems shown in Table 15-3-2. The basic unit is called the unit cell and a relationship exists between the characteristics of the unit cell and the shape of the crystal.

Table 15-3-2

DATA ON CRYSTAL SYSTEMS

Cubic, or Regular	Three axes at right right angles: all equal.	Monoclinic	Three axes, one pair not at right angles: unequal.
Tetragonal	Three axes at right angles: two equal.	Triclinic or Anorthic	Three axes not at right angles: unequal.
Orthorhombic or Rhombic	Three axes at right angles: unequal.	Hexagonal	Three axes coplanar at 60°: equal. Fourth axis at right angles to other three.
		Rhombohedral or trigonal	Three axes equally inclined, not at right angles: all equal.

CRYSTALS OF METALS

Metals tend to crystallize in simple patterns which lead to efficient "packing" of equal spheres. Two examples of packing are shown in Figure 15-3-2 (a) and (b). Figure 15-3-2(a) shows a hexagonal close-packed structure, a lattice arrangement common to most metals, which is built of tightly nested layers of atoms. Three layers of hexagons provide the 17 atoms which form the crystal unit. Atoms in the layer A fall directly over one another. Three atoms in B next between them. Figure 15-3-2(b) shows how an alternative close-packed structure can be built from layers of hexagons in the sequence ABCA. In this arrangement, 12 atoms can be selected that form a face-centered cube with the same packing density as the hexagonal close-packed structure. Metals commonly crystallize in either the hexagonal, the face-centered, or body-centered-cubic configuration.

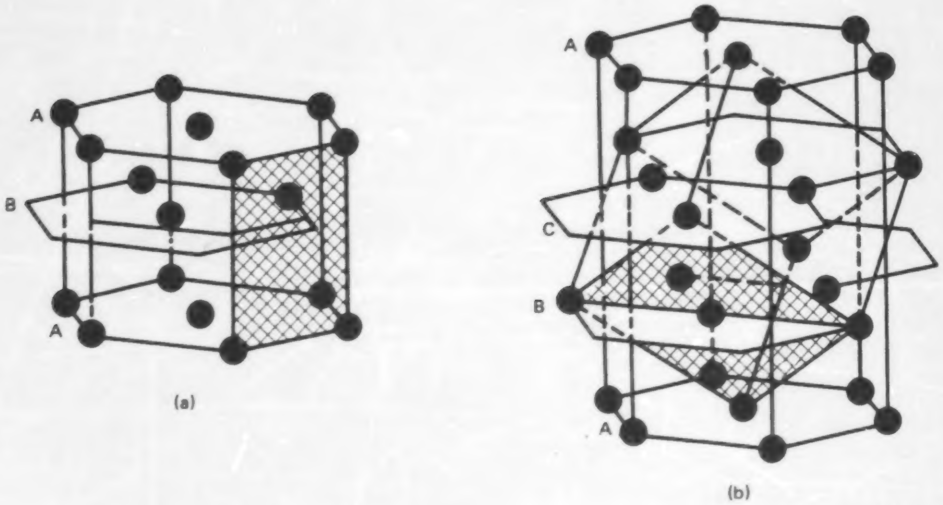


Figure 15-3-2 Crystals in Metals

LATENT HEAT OF FUSION

If the temperature of a solid is raised, the amplitude of vibration of the atoms increases. This increase is usually accompanied by an increase in volume. With a sufficient rise in temperature, this amplitude of vibration becomes so great that atoms escape from the attraction of their neighbors to form a liquid state as sketched in Figure 15-3-3.

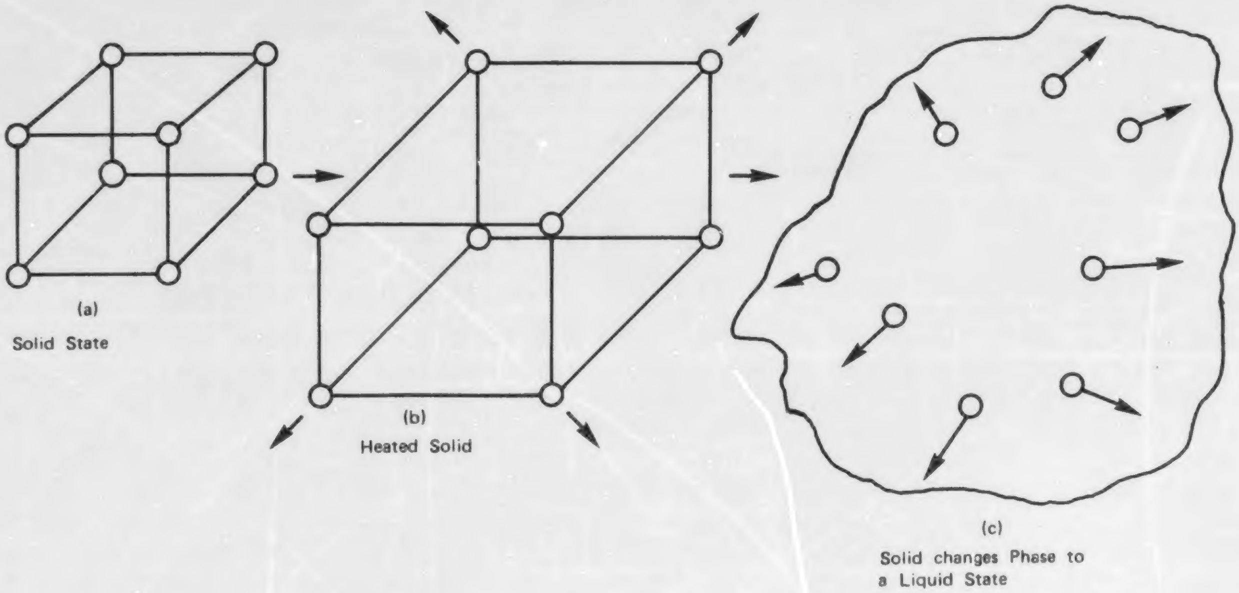


Figure 15-3-3 Phase Change Sketch of a Solid Being Changed to a Liquid

Atoms can exist in orderly pattern (solid state) with less energy. The amount of energy given up by a system when it solidifies equals the amount that must be given to it when it melts. This energy, called "heat of fusion," produces no rise of temperature (equilibrium), but only a change of state. Frequently, it is called the "latent heat of fusion."

If temperature is adjusted until equilibrium between the liquid and solid is attained (e.g., the rate of freezing equals the rate of melting), the system is said to be at its melting point.

EQUILIBRIUM

Often a misunderstanding results from too narrow an interpretation of the word "equilibrium," which comes from two Latin words meaning "equal balance." It is correct to speak of a brick lying on its broadest face as being in equilibrium. This is a static condition - no motion is involved. But equilibrium is not restricted to a static condition. For instance, because a chemical reaction reaches equilibrium does not mean the reaction has stopped. What has happened is that the rate of formation of the product (or products) from the reacting substances is equaled by the rate of decomposition of the product into the reacting substances. The rate of forward reaction just equals the rate of backward reaction, and the quantity of the product is constant (Figure 15-3-4). The occurrence of a chemical reaction, like the raising of a brick, is accompanied by a change in energy. The real test for equilibrium is to determine what state of a system has the lowest energy for a given set of external conditions of temperature and pressure. This determination may be easy, as in the example of the brick, or it may be difficult, as in the determination of the equilibrium state of an alloy at room temperature.

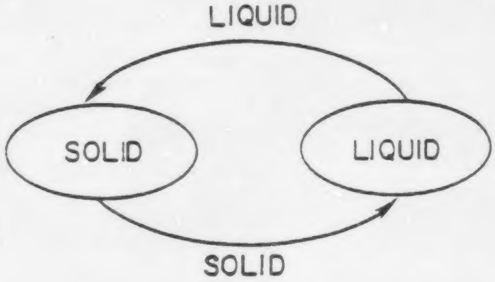


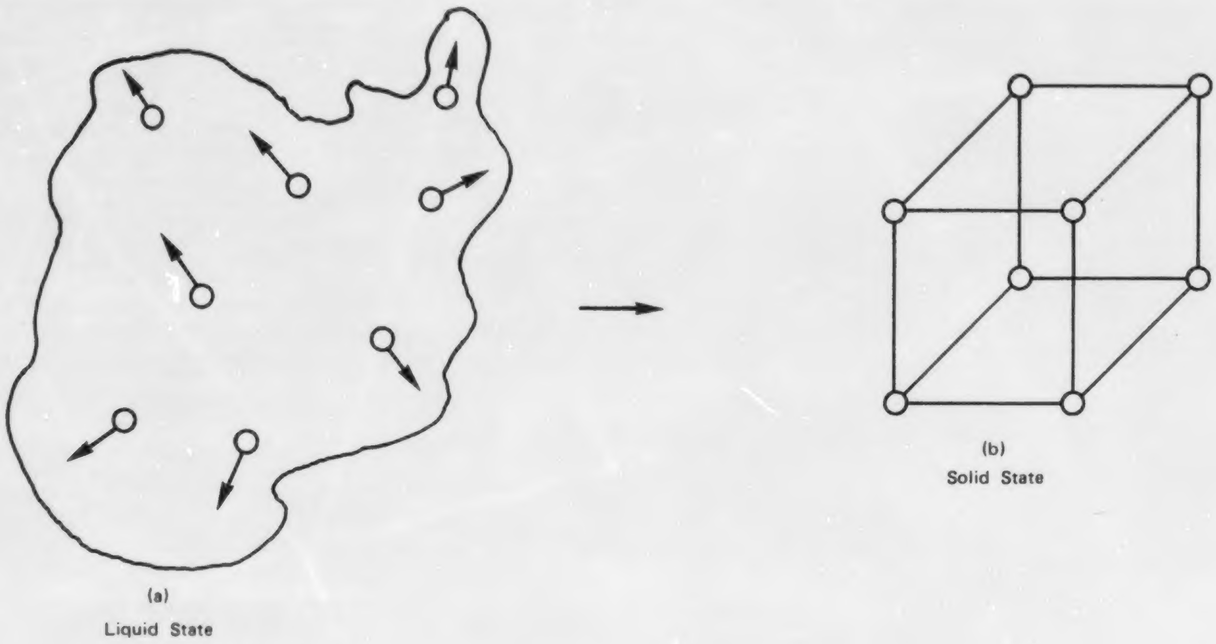
Figure 15-3-4.
Equilibrium.

SOLIDIFICATION

If a liquid is heated to a temperature above that at which all the solid is melted, then cooled without disturbance, it ordinarily drops to a temperature below that of solid-liquid equilibrium. Additional undercooling or supercooling may be necessary before some chance grouping of the rapidly moving atoms approximates the proper geometric arrangement for the nucleating of a crystal.

This group of atoms must be large enough initially to survive, even though some of its atoms happen to acquire enough energy to escape from the surrounding atoms of the liquid. With little supercooling, few, if any, chance groups survive; but with the whole system cooled to a lower temperature, the vibration of all atoms is decreased and more chance groups survive and grow, atom by atom.

The more rapidly a liquid is cooled, the further it supercools, and the greater the number of crystal nuclei. This "rate of nucleation" tends to increase with a greater amount of supercooling. If heat is continuously removed from the system, because of its contact with cooler surroundings, more nuclei form and grow until the growing crystals touch each other and finally convert all of the disordered liquid to the solid state as depicted in the simplified sketch shown in Figure 15-3-5. There will be as many crystals or grains in the system as there were surviving or stable nuclei.


(a)
Liquid State

(b)
Solid State

Figure 15-3-5 As Heat is Removed the Nucleation Process Begins Where the Liquid is Transformed into a Solid.

If this process is thought through carefully, it may be observed that rapid cooling tends to produce more crystals (and smaller crystal sizes) than slow cooling. One more step in the reasoning will then make it evident that the designer will do well to give some consideration to the thickness of sections in a casting; thin sections cool faster, supercool more and tend to result in finer-grained castings.

PHASES

A phase is a homogeneous portion of matter existing as a single state, made up of one or more components and separated from every other phase by an interface. The state of a phase may be solid, liquid or gaseous. A system is homogeneous if it consists wholly of one phase, whether that phase is continuous or not. Thus, a single-phase solid may consist of one crystal or many crystals. And a liquid may or may not be broken up into several pools or into many droplets.

A system wholly in the gaseous state must consist of one phase; interfaces between various vapors are not possible.

A system of two or more phases is heterogeneous. Muntz metal, an alloy of 60% copper and 40% zinc, is heterogeneous at room temperature; i.e., it is made up of two different types of crystals. Each type, with a different composition and a different atomic arrangement, constitutes a phase. A specimen may have one crystal of each phase, or many of each. By changing the ratio of copper to zinc, the relative amounts of the two phases can be varied from 100% of one phase to 100% of the other phase. Neither phase can change composition at room temperature while the two phases are in equilibrium. The shape and extent of the interface between the two phases can be changed, but there must remain an interface wherever the two meet.

SOLID SOLUTION.

A pure element or pure compound solidifies in a geometric pattern characteristic of that element, forming a single solid phase. A system containing only one element or one pure compound is a one-component system. A system containing two components may do one of several things, depending on the individual components and their concentrations in the liquid.

Copper and nickel, solidified independently, crystallize with almost identical geometrical arrangements and spacings of their atoms, and they are also very similar chemically. If the two elements are melted together in any proportion and allowed to solidify, it is found that only one kind of crystal forms, in a single solid phase.

Copper atoms and nickel atoms are used almost without selection or discrimination. The growing crystal prefers the nickel atom, but not enough to cause two separate kinds of crystals to form, regardless of the initial concentration.

A solid phase, formed by two or more kinds of atoms over a range of variation of concentration, as though all atoms were of approximately the same kind, is called a solid solution.

Not many pairs of metals form solid solutions through any and all concentrations; many pairs of metals form solid solutions over a limited range of compositions, and some pairs have such a minute degree of solid solubility as to be classified as insoluble in that state. For example, solid copper dissolves unlimited amounts of nickel, up to 32.5% of zinc, 13% of tin, 07.4% of aluminum, 0.7% of silver, 0.3% of cadmium or 0.1% of zirconium, but practically zero amounts of lithium (all amounts measured just as solidification is completed).

In each of the above cases, a crystal that contains a maximum possible concentration of the second component (for example, copper containing 32.5% of zinc) is said to be saturated. One containing a lesser amount (10 or 17 or 29% zinc in copper) is undersaturated (or, more simply, unsaturated).

In either saturated or unsaturated crystals, the geometric pattern is of the same type as that of pure copper, except that a slight distortion of the pattern occurs at the location of each solute atom.

Because copper establishes the pattern, it is called the solvent. If an attempt is made to grow crystals having a concentration of solute slightly greater than the limit of solubility, saturated crystals are produced (with the excess solute left temporarily in the liquid state), together with some definite concentration of solvent atoms. Just how this liquid subsequently solidifies cannot be described by a generalization. The several types of behavior must be discussed individually because the minimum energy (equilibrium) state depends upon the kinds of atoms put into the system, as well as upon their respective concentrations.

SOLIDIFICATION OF ALLOYS

Two features of a system, besides composition or concentration, are of principal interest: pressure and temperature. These are often termed external conditions because external means are used to control them.

In metallurgical operations, a temperature range of thousands of degrees is utilized; service conditions vary by hundreds of degrees. For purposes of this module, temperature is considered to be a measure of the amplitude of vibration of the atoms making up the system.

SOLID-LIQUID EQUILIBRIUM

The important point at the moment is to get a clear picture of equilibrium. Does composition affect freezing? To answer this question, follow an example in which one component, copper, is the solvent and the other component, zinc, is the solute.

Assume that pure molten copper is contained in one crucible and that successive crucibles contain melts of copper with, respectively, 10%, 20%, 30% and 35% zinc. While they are liquid, one phase exists in each system. (They should be cooled with extreme slowness, because the maintenance of even an approximation of equilibrium requires a very gradual change in external conditions.) As the procedure progresses, a few crystals of pure copper form in the first crucible. This crucible is now heterogeneous; i.e., two phases are present.

As more heat is lost to the surroundings, more copper crystals form, but the temperature remains constant at 1981°F (1082.8°C) as long as liquid copper and solid copper are in equilibrium. When the last of the liquid has solidified, the temperature may again start to fall. At this time, none of the other crucibles will contain crystals.

As the temperature falls to 1920°F (1048.9°C), the first solid solution crystal appears in the 10% zinc alloy; at 1830°F (998.9°C) crystals appear in the 20% zinc; at 1740°F (948.9°C) they appear in the 30%. There is one, and only one, temperature at which a given concentration of liquid solution of two components can be in equilibrium with a crystal (Figure 15-3-6).

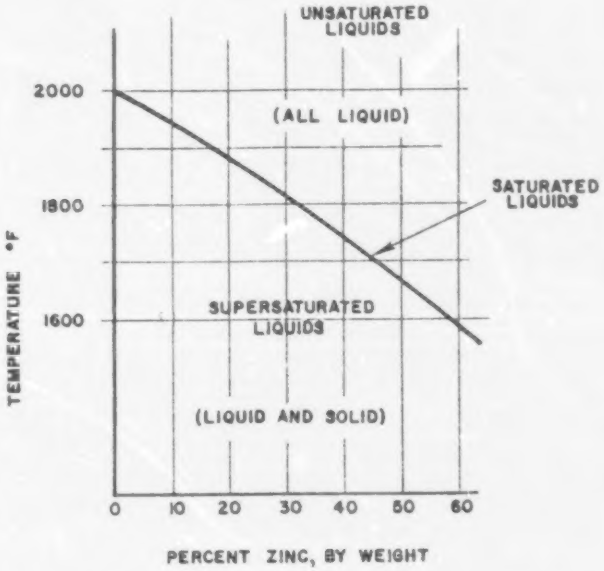


Figure 15-3-6.
Saturation curve for
copper-zinc liquid.

A liquid in equilibrium with a solid is a "saturated" liquid. Any copper-zinc liquid composition is unsaturated when its temperature is above the curve, saturated if on the curve and supersaturated if below the curve. Conversely, if a given temperature is selected, all compositions of greater concentrations than those shown by the curve are unsaturated, but are supersaturated at concentrations lower than that of the curve.

The crystal phase must have a composition different from that of the liquid in equilibrium with it, except in the case of a molten pure element or pure compound. The mutual influence of an atom on its neighbor's atomic interaction is not the same in the orderly state of the solid as in the disorganized state of the liquid.

In the unique case of a pure element or a pure compound, only one kind of material is present, as the system is made up of a single component. Both the liquid and the solid must be composed of it, for nothing else is present. Refer once more to the crucibles of copper-zinc alloys. When the 10% zinc liquid became saturated at 1920°F (1048.9°C), the solid phase, in equilibrium with the liquid phase, contained 8.5% zinc. The solid, in equilibrium with the 20% zinc liquid at 1830°F (998.9°C), contained 17% zinc; and at 1740°F (948.9°C), a 25% zinc solid saturated the 30% zinc liquid. The only liquid that can coexist with a saturated crystal of 32.5% zinc must contain 38.5% zinc, and the temperature must be 1660°F (904.4°C).

These results can be plotted (Figure 15-3-7). An isotherm (constant temperature line), drawn horizontally to cut the curves at any temperature between 1660 and 1981°F (904.4° and 1082.8°C), connects the composition of the solid phase (lefthand curve) and the composition of the liquid phase (righthand curve), which are in equilibrium at the selected temperature.

The isotherm connecting graphical location of the two phases is called a tie line. The pair is in equilibrium only at the selected temperature. The righthand curve (liquidus) is the locus of all the saturated liquid compositions. The lefthand curve (solidus) is the locus of the solids that

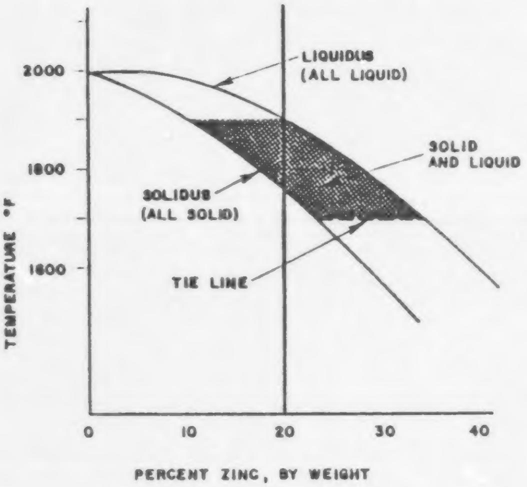


Figure 15-3-7. Solid-liquid equilibrium diagram for copper-zinc alloys.

are in equilibrium with liquids (i.e., solids that saturate the liquids).

Suppose the 20% zinc alloy is remelted, which requires that it be heated to at least the temperature of the liquidus. This temperature can be found by drawing a vertical or constant-composition line at 20% zinc (Figure 15-3-7). Now, assume that the 20% zinc alloy is slowly cooled - its temperature falls so slowly that equilibrium is approximated. When the temperature drops slightly below the liquidus, the liquid is slightly supersaturated, and a crystal is nucleated. Because this crystal requires a composition slightly different from that of the liquid, a few excess zinc atoms remain in the adjacent liquid. Further solidification is temporarily halted until thermal (convection) currents and the natural motion of the atoms distribute these excess zinc atoms uniformly throughout the liquid, slightly increasing zinc content of the whole liquid so that it is again just saturated. At this time it is again in equilibrium with the solid, and solidification occurs at exactly the same rate as the melting occurs.

If a little heat is again lost to surroundings so that the contents of the crucible cool slightly (a new tie line may be drawn at this new temperature), the liquid again becomes slightly supersaturated, and a few more atoms join the solid phase. This new layer of crystal, formed from a liquid with higher zinc content, evolves at a lower temperature than did the nucleus.

To be in equilibrium with the liquid, this new layer must contain a slightly higher percent of zinc than that contained in the nucleus. Thus, at this new temperature, the surface layer of the solid is in equilibrium with the liquid; but the core of the crystal is not in equilibrium with the surface layer. Given time, these two zones will exchange atoms and, if necessary, acquire other atoms from the liquid until all of the solid is in equilibrium with the liquid. This movement of atoms, restoring uniformity of composition, is known as "diffusion."

By continuation of the steps described above, the liquid solidifies, layer upon layer, with the occasional nucleation of a new crystal. Note that the process requires a decrease in temperature for continuance of solidification. If the fall in temperature is stopped, solidification stops. The very process of solidification increases the percent of zinc in the liquid; only by cooling can it be maintained in a supersaturated condition.

Note also that the solid gradually increases in percent zinc. Eventually, it will increase to 20%, the composition of the original alloy. Since the average composition of solid plus liquid is identical with the composition of the whole alloy, there must be a zero amount of liquid present when all the solid contains 20% zinc. Similar reasoning may be used to trace the equilibrium solidification of melts in the other crucibles.

The process just described - solidification of the alloy - is followed when approximate equilibrium is maintained. The time required for diffusion to keep the liquid homogeneous is rather great.

No casting of copper-zinc alloys made in a foundry is homogeneous. To control industrial operations, the tendencies of nature's processes (i.e., equilibrium) must be known before the processes can be incorporated into production.

A brief study of steps in the process of solificication (under nonequilibrium conditions) illustrates the probable manner of application to foundry casting. Assume a 20% zinc alloy of copper, melted and poured into a sand mold. The cold sand removes a considerable amount of heat from the liquid immediately upon contact, but the interior portion of the liquid remains quite hot. Solidification does not start when the liquid cools to the liquidus temperature, as the surface liquid may be supercool many degrees before it becomes unstable enough to nucleate crystals spontaneously. (At the melting point, the liquid and the solid are equally stable. Above the melting point, the liquid is the more stable state; below that temperature, the liquid is less stable than the solid.) Even the center of the casting probably cools to the liquidus temperature by the time, at the surface, nuclei begin to form and grow.

Because a crystal is an orderly geometric pattern, atoms attach themselves more readily on some faces than on others. Nuclei formed with their preferred faces toward the supplying liquid quickly crowd out nuclei less favorably oriented, casting them off from their source of atoms.

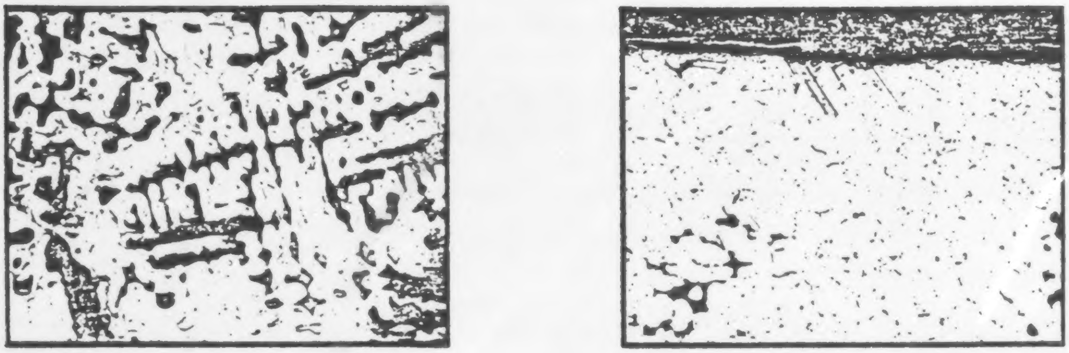
Supercooling allows growth to continue into the liquid state in spite of the buildup of these excess zinc atoms (although growth is retarded wherever the liquid becomes overconcentrated with zinc atoms).

Two opposing tendencies are now at work: the crystals grow by additions of layers on regular geometric faces, and growth is most rapid in areas of ideal composition and temperature. The result is a skeleton-like crystal (resembling a pine tree with a central trunk and branches) called a "dendrite," from the Greek "dendron," meaning tree. The ties of the trunk and branches grow faster, being exposed to convection currents and diffusion from all sides, and growth requires that the excess zinc atoms be taken away. The zinc is more likely to accumulate in the pockets between the branches, where it retards growth until a lower temperature is reached.

Because almost no zinc was carried into the cores of the crystals by diffusion after solidification, solidification continues to a lower temperature than that predicted (Figure 15-3-7). Cored crystals result from solid solutions when solidification occurs at a faster rate than that of diffusion. If the casting is reheated to a temperature close to melting and held there for a long time, the solute atoms tend to diffuse toward the core of each crystal; solvent atoms diffuse in the opposite direction. Given enough time, each crystal approximates homogeneity (Figure 15-3-8).

It might be erroneously assumed that slow solidification (giving more time for diffusion) results in a more nearly homogeneous casting, that is, in less segregation. Two points are overlooked when such an assumption is made.

First, rapid solidification is more likely to induce a considerable degree of supercooling of the liquid. Nu-



AS CAST

AS HOMOGENIZED FOR 24 HOURS AT 1600 °F

Figure 15-3-8. Silicon bronze.

cleation rate of crystals is more rapid and, since more crystals compete for the liquid, the final crystals are smaller. Thus, the distance over which atoms must diffuse is smaller and the composition gradient from core to surface of each crystal is steeper. To gain these advantages, chill-cast ingots (cast in iron molds) are usually made. Rarely is an attempt made to homogenize sand castings of nonferrous alloys.

A second advantage of rapid solidification is that columnar dendrites form to a considerable depth. The main thrust carries the low-solute core of each crystal well into the casting, and the pockets between branches distribute the excess solute in a random fashion. Even a very slow rate of solidification disallows enough time for really effective diffusion; rather, it tends to produce much larger crystals, and more of the excess solute concentrates in the center of the casting.

Industrial processes employed to produce and fabricate metallic articles are concerned with liquid, solid and, occasionally, vapor states of metals. The interrelation of phases is the main determinant of alloy characteristics and the way they respond to operations performed on them. Because almost every industrial operation is conducted as an art (depending heavily on the skill of the worker), it is assumed that the worker controls the reactions. Actually, nothing of the sort happens. The most basic lesson one can learn from science is that the result of every operation and every reaction is the only one possible for the combination of components used and the conditions existing at that time.

(It is not the intention here to minimize the importance of know-how. The point is that, whether experience or theory is applied, the goal should be to learn, as far as possible, the laws of nature.)

A valuable lesson in metallurgy can be learned from a bowl of hot vegetable soup. The oily droplets may be herded together and merged into floating islands or broken up into many separate particles; there is no permanent interface within one phase. But, at a given temperature, the boundary between the two phases is always sharply defined.

If salt, another component, is added to the soup, it dissolves. Most of it enters the water phase, but a little goes into the oily phase. There is a partition of the added component (salt) between the two phases.

EXERCISES

None.

MATERIALS

Furnace.
Furnace crucibles.
Thermocouples.
Potentiometers.
Pure copper.
Zinc materials.
Lead materials.
Tin materials.
Balance.

PROCEDURES

LEAD-TIN ALLOYS

1. Alloy 3 pounds of lead with 1 pound of tin.
2. Heat to above 510°F (265.6°C) to form a homogeneous liquid of 25% tin and 75% lead.
3. Cool to below 510°F; as alloy begins to solidify, add

tin to it; alloy should remelt. (Conversely, an 80% tin alloy, at 400°F, will start to solidify if tin is added.)

These procedures demonstrate that we can change the conditions, but nature decides the results.

4. Heat 1 pound of tin to above its melting point, then allow it to cool slowly in air. Use thermocouple to measure temperature at which solid crystals are first noticed; record temperature on Data Table 15-3-1; also, record temperature at which the entire mass becomes solid. (Be sure to keep the mass "mixed.")
5. Repeat 4, above, using the following materials and quantities:
    - 1 pound of lead.
    - 1/4 pound of lead and 3/4 pound of tin.
    - 1/2 pound of tin and 1/2 pound of lead.
    - 3/4 pound of lead and 1/4 pound of tin.

DATA TABLE

DATA TABLE 15-3-1

Weight of Constituents lbs		Liquidus Temp °F	Solidus Temp °F
Lead	Tin		

REFERENCE MATERIALS

Johnson, C.G. and Weeks, W.R. Metallurgy. Chicago: American Technical Society, 1977.

Simons, E.N. An Outline of Metallurgy. New York: Hart Publishing Company, 1969.

TEST

Read each question carefully. Be sure to provide the specific information each question requires. Your answers should be brief.

1. Describe how atoms go from a solid state to a liquid state.

2. What is the melting point of any system?

3. What does the term "equilibrium" mean?

4. What effect (if any) does a liquid's cooling rate have on the formation of crystals and crystal size?

5. What does the term "phase" mean?

6. If any proportion of the two elements copper and nickel is melted together and then allowed to solidify, how many kinds of crystals are formed?

7. What is a solid solution?

8. Answer these questions about the processes taking place as atoms go from a liquid state to a solid state:

   a. When do nuclei begin to form?

   b. What causes nucleation to increase?

   c. When is the rate of crystal growth greatest, relative to the rate of nucleation?

   d. What causes nucleation and growth of crystals to stop?

9. Answer these questions about solid solutions:

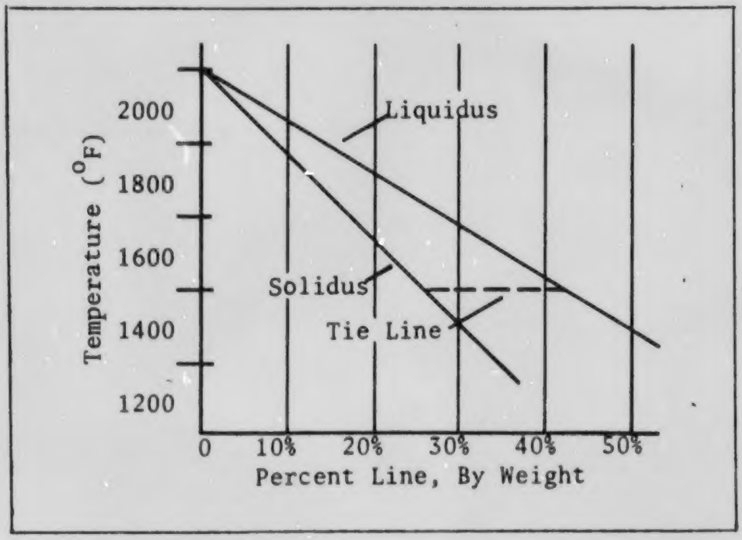
   a. What is the difference between the solute and the solvent?

   b. What happens to electrical and thermal conductivity when the solvent accepts solute atoms?

   c. Describe the net movement of the solute atoms when diffision occurs in a solid solution.

10. What causes the cored structure crystals that often result from non-equilibrium cooling?

11. Here is a saturation curve for a copper-zinc solution. Use the curve to answer the questions below and on the next page:



a. At how many temperatures can a given concentration of liquid solution of the two components lie in equilibrium with a crystal?

b. As shown on the saturation curve above, when is any copper-zinc solution saturated?

c. As shown on the saturation curve above, when is any copper-zinc solution supersaturated?

d. As shown on the saturation curve above, when is any copper-zinc solution unsaturated?

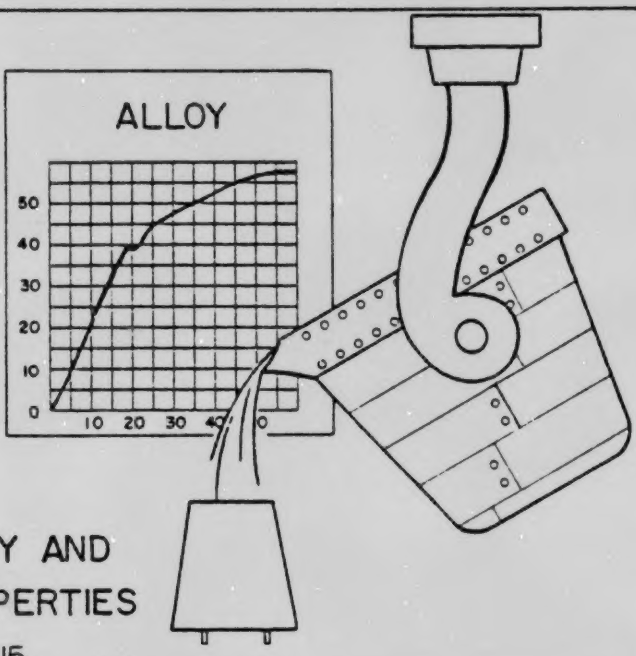
e. When two or more phases are present, what word is used to describe the system?

f. What is the purpose of the Tie Line?

g. Describe the solution in the region between the liquidus and solidus:

NUCLEAR TECHNOLOGY

MODULE 15-4 PROPERTIES OF STEEL


ALLOY
50
40
30
20
10
0
10
20
30
40

METALLURGY AND
METALS PROPERTIES
COURSE 15

COURSE MODULES

COURSE 15 METALLURGY AND METALS PROPERTIES

MODULE 15-1	Fabrication Processes for Metals
MODULE 15-2	Chemical Analysis of Metals
MODULE 15-3	Basic Metallurgical Concepts
⇨ MODULE 15-4	Properties of Steel
MODULE 15-5	Metallographic Examination
MODULE 15-6	Mechanical Testing - Tensile, Bend Hardness
MODULE 15-7	Mechanical Testing - Impact, Nick Break Fatigue
MODULE 15-8	Failure Mechanisms in Metals

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INTRODUCTION

The versatility of steel is attributable in large measure to its response to a variety of thermal treatments. While a major percentage of steel is used in the "as-rolled" condition, thermal treatment greatly broadens the spectrum of properties attainable. This module explores the properties of steel and also reviews the processes and terminology associated with steel production.

The thermal treatment of steel falls into two general categories:

1. Those which increase the strength, hardness and toughness by virtue of rapid cooling from above the transformation range.
2. Those which decrease hardness and promote uniformity by slow cooling from above the transformation range, or by prolonged heating within or below the transformation range, followed by slow cooling.

The first category involves hardening by quenching and tempering, or a variety of specialized treatments undertaken to enhance the hardness of the surface to a controlled depth. Whereas the second category encompasses normalizing and various types of annealing, the purpose of which may be to improve machinability, toughness, or cold forming characteristics, or to relieve stresses and restore ductility after a processing which has involved some form of cold deformation.

Further, the effect of alloying on the microstructure of steel is also examined, along with the optimum rate of quenching. In addition, the fact that both the alloying process and the quenching process affect other processes, such as annealing, tempering and austempering will also be considered.

MODULE PREREQUISITES

The student must have successfully completed Modules 15-1, "Fabrication Processes for Metals," 15-2, "Chemical Analysis of Metals," and 15-3, "Basic Metallurgical Concepts."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Describe or define a) mechanisms (of rapid cooling of steel) that produce a martensite structure, b) hardenability and critical cooling rate, c) limitations of quenching, d) factors affecting hardenability and e) method of measuring hardenability.
2. Describe a low-alloy steel; list at least two applications.
3. Briefly describe effects of alloying elements on tempering, austenite retention and the temperature at which martensite forms (M_s point).
4. Describe effect of slow cooling (through certain temperature ranges) that produces brittleness in material.

5. List or describe reasons for using the following processes:
    - Annealing -
        - Homogenizing.
        - Full annealing.
        - Normalizing.
        - Cyclic treatment.
    - Hardening/tempering -
        - Martempering.
        - Austempering.
        - Tempering.
6. Describe resistance heating as applied to field heat-treating operations.

GLOSSARY

The following glossary of terms should allow the student to better understand the processes described in this module:

Allotropic - Having two or more structures that are stable in different temperature ranges (e.g., different crystalline forms of carbon).

Anneal - Treat a metal or alloy with heat, then cool to remove internal stresses and make material less brittle.

Austempering - Heat treating austenite (see "tempering"). It is the quenching of a ferrous alloy from a temperature above the transformation range, in a medium having a rate of heat abstraction high enough to prevent the formation of high temperature transformation products, and then holding the alloy, until transformation is complete, at temperature below that of pearlite formation and above that of martensite formation. (See pearlite and martensite).

Austenite - A solid solution of one or more elements in a face-centered cubic iron. Unless otherwise designated, the solute is assumed to be carbon.

Austenitic - Composed mainly of austenite.

Austenitic steel - An alloy steel whose structure is normally austenitic at room temperature.

Austenitize - To heat steel to the temperature range in which the crystalline form of iron is austenite.

Ductility - The ductility of a material is that property which permits it to be drawn into a wire. The smaller the diameter of the wire to which it can be drawn, in general, the greater the ductility. In wiredrawing steel it is a common practice to anneal (heat treat) the wire between successive passes through the die.

Eutectoid - A mixture of phase, the composition of which is determined by the eutectic point (lowest melting point) in the solid region of an equilibrium diagram and whose constituents are formed by the eutectoid region.

Eutectic - The microstructure that forms when a metal of eutectic composition solidifies.

Hardenability - In a ferrous alloy, the property that determines the depth and distribution of hardness induced by quenching from elevated temperatures.

Hardness - The resistance of a metal to plastic deformation usually made by indentation. However, this term may also refer to stiffness or temper, or to resistance to scratching, abrasion or cutting.

Homogenize - To hold metal at a high temperature long enough to eliminate (by diffusion) any chemical segregation of the components.

Malleability - The property of a material that makes it capable of being rolled or hammered into thin sheets of various shapes, or being extended or shaped by the pressure of rollers or dies is called malleability.

Martempering - Quenching austenitized steel to a temperature just above, or in the upper part of, the martensite range, holding it at this point until the temperature is equalized throughout, then cooling it in air to room temperature.

Martensite - In carbon steel, a hard, supersaturated solid solution to a carbon in a body-centered tetragonal lattice of iron.

Martinsitic - Quenched carbon steel composed chiefly of martensite.

Matrix - The principal phase or aggregate in which another constituent is embedded.

Pearlite - A laminar (layered) aggregate of ferrite (almost pure iron) and cementite (Fe_3C) often occurring in carbon steels and in cast irons.

Quench annealing - Annealing an austenitic ferrous alloy by heating, followed by quenching from solution temperatures.

Quench hardening - Hardening a ferrous alloy by quenching from a temperature above the transformation range.

Quenching - Cooling (heated metals) by immersion (in oil or water).

Tempering - Heat treating hardened steel to a temperature below the transformation temperature range, usually to improve toughness.

Toughness - Ability of a metal to absorb energy and deform plastically before fracturing.

HARDNESS

The hardness of a material or object is described, in terms of the molecular theory of matter, as the internal resistance of the material or object to having its molecules forced farther apart or closer together.

Hardness is checked in many ways. The simplest is by a scratch test where the harder of two materials will leave a scratch on the softer material. Mohs' scale of hardness sets standards for ten materials and scratches on other materials are checked for hardness against the standards.

Table 15-4-1 shows the Mohs' Scale of Increasing Hardness and Table 15-4-2 shows a listing of the Mohs' Values for Structural Materials. Note that the increasing value of Mohs denotes increased hardness.

Table 15-4-1

Mohs' Scale of Hardness

1. Talc
2. Rock salt or gypsum
3. Calcite
4. Flourite
5. Apatite
6. Feldspar
7. Quartz
8. Topaz
9. Corundum
10. Diamond

↓ Increasing Hardness

Table 15-4-2

Mohs' Values for Structural Materials

Aluminum	2.0 - 2.9
Brass	3.0 - 4.0
Emery	7.0 - 9.0
Iron	4.0 - 5.0
Lead	1.5
Marble	3.0 - 4.0
Steel	5.0 - 8.5
Tin	1.5 - 8.0

Hardness of a metal is typically measured by indentation of the metal by same method. Indentation hardness is usually measured by such tests as Brinnel or Rockwell.

The Brinell test involves pressing a 10-mm hardened chrome-steel ball into the test specimen with a force of 29,400 Newtons. The resulting indentation is measured and the material assigned a number denoting its hardness. The larger the number, the harder the material.

$$\text{Brinnell Number} = \frac{\text{Force (Newtons)}}{\text{Surface area of indentation } (\text{mm}^2)}$$

Table 15-4-3 shows the Brinell Hardness of several materials.

Table 15-4-3

Brinnell Hardness of Materials

Material	Brinell Number
Aluminum, annealed	16
Chromium	91
Copper-Aluminum (11.73%), hard-rolled	269
Iron, annealed	77
Lead, cast	4.2
Platinum, drawn	64
Carbon steel	460
Alloy steel-nickel-vanadium-carbon-manganese-silicon	627

The Rockwell hardness machine uses different pointed indenters which are dropped on the material and the degree of indentation is then measured. A diamond cone is used for hard materials while chrome steel cones are used for softer materials.

The Bessemer process of producing steel evolved from the conventional method of producing steel by heating and then rapid cooling by plunging the hot steel into the water or oil. The problem arose from the steel becoming too brittle for most applications. The Bessemer process involved tempering (toughening) the steel by reheating and cooling slowly. The degree of tempering and thus the required toughness was checked by plunging the cooling metal into cold water or an ice bath. Metals treated in this manner lose hardness but become tougher.

The same procedure is followed in the process called annealing. The metal is allowed to cool slowly and completely. It is left soft and tough but not brittle.

Hardness and brittleness are sometimes confused. Steel is made hard and tough while glass is relatively hard but brittle. The dictionary defines brittle as being hard but not tough. The material is easily broken, cracked or snapped.

In the sections which follow hardenability in steel will be considered. Hardenability determines the depth and distribution of hardness induced by quenching.

HARDENABILITY OF STEELS

Most steel is used in its as-rolled condition, without subsequent heat treatment. A relatively small percentage of all steel produced must be heat treated to improve one or more of its specific mechanical properties. Much of this heat treated steel is used in parts that must have high strengths and toughness, rather than maximum hardness. These parts are austenitized, then quenched to produce martensite as shown in Figure 15-4-1 and, finally, tempered at high temperatures.

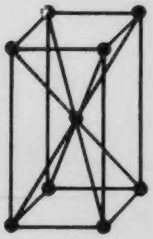


Figure 15-4-1 Martensite Structure is a Body Centered Tetragonal Crystalline Arrangement.

HARDENABILITY

Hardenability (not to be confused with hardness) of martensite depends upon its carbon content (Figure 15-4-2).

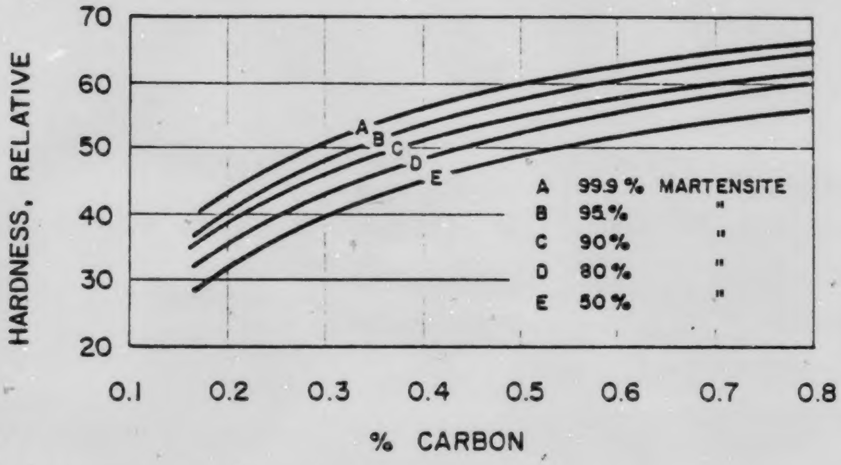


Figure 15-4-2. Average relationships of hardness to percentage of martensite.

If steel is to be hardened to a martensite structure, it must first be austenitized, then cooled at a rate sufficient to prevent the formation of ferrite, pearlite and bainite (highly ductible steel). The slowest cooling rate that avoids all three nonmartensitic decomposition products of austenite is called the "critical cooling rate," which varies considerably with steel composition.

A few steels form martensite when cooled at only five degrees per second. Others must be cooled more rapidly, some in excess of 1100°F per second. A steel that requires a rapid cooling rate to produce martensite is said to have low hardenability.

Hardenability, then, may be regarded as a measure of the ease of obtaining martensite (of attaining hardness values shown by the curve). But hardenability does not affect the shape of the curve. A 0.40% carbon steel, if fully martensitic, has only one hardness value, whether the steel is of low or of high hardenability. Also, if heat treated to a fully martensitic structure, it is harder than a 0.40% carbon steel of high hardenability, which is also fully martensitic.

LIMITATIONS OF QUENCHING

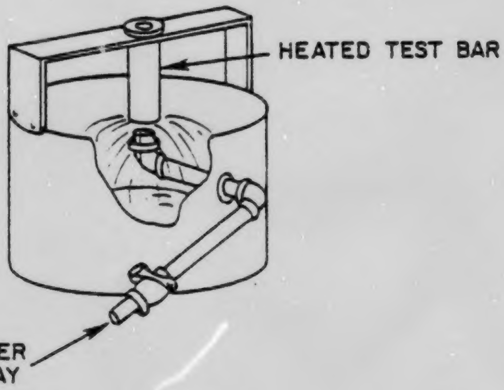
Because steel is a fairly good conductor of heat, it is erroneously assumed by some that quenching in water produces a rapid rate of cooling in the interiors of thick sections. Steels of low hardenability respond to heat treatment for only a limited depth when thick sections are quenched; such steels are said to be shallow hardening. Even their surfaces may not be fully hardened unless the movement of water past the surfaces is vigorous enough to flush away the steam envelope.

MEASUREMENT OF HARDENABILITY

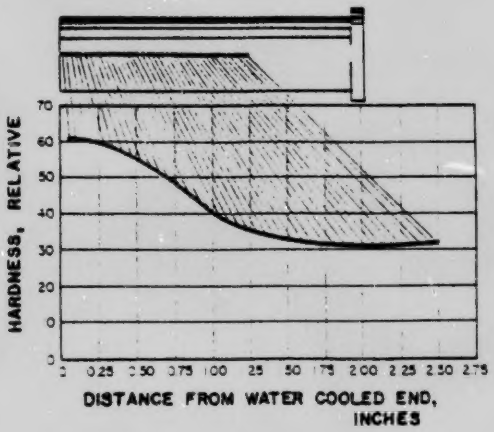
The Jominy end-quench test is most commonly used to measure hardenability of common alloy steels. It allows a simple, cylindrical bar to be subjected to all cooling rates between 4 and 600°F per second. (The "rate" is that at which the steel cools past 1300°F.)

A one-inch diameter bar 3 or 4 inches long, with either a cap screw or a shoulder, is suspended vertically (Figure 15-4-3). After being heated uniformly to the proper quenching temperature, the bar is placed on the fixture, and a gentle jet of water is directed against its lower end (no water touches the cylindrical surface) until the entire bar is cooled.

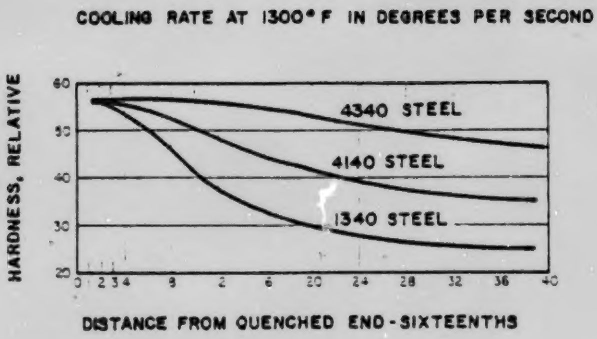
Figure 15-4-3.
End-quenching fixture.



A flat is ground along two diametrically opposite sides of the cylinder to remove any decarbonized surface. Hardness readings are made every one-sixteenth inch for the first inch from the quenched end, then every quarter inch for the remainder. The readings are plotted as ordinates (vertical scales) against distance-from-quenched-end as abscissae (Figure 15-4-4).



Typical depth-hardness curve plot.



Three typical steel depth-hardness curves.

Figure 15-4-4. Jominy end-quench test results.

FACTORS AFFECTING HARDENABILITY

Since the introduction of the procedure in 1938, thousands of Jominy tests have been made on many types of steels. From a correlation of a large number of these test results, many of the characteristics of steel (that affect hardenability) can be evaluated.

Carbon content of steel or, more specifically, the amount of carbon in solid solution in austenite, is the most important factor; that is, hardenability increases with increased carbon content, and reaches a maximum at eutectoid composition; then it decreases, with still higher percentages of carbon.

Pearlite, the structure to be suppressed by quenching, tends to nucleate at austenite grain boundaries. The coarser the austenite, the smaller the total grain boundary area, and the greater the hardenability.

Also, materials which have been machined also tend to lose hardness because the surface of the metal tends to be harder than the grain structure within the metal specimen. As a result, machined materials must often receive heat treatment to restore them to their original hardness.

LOW-ALLOY STEEL

Steels containing moderate amounts of alloying elements are used principally for structures such as bridges, railroad cars and ships, and for machine parts that are to be heat treated, i.e., hardened and tempered. In tonnage produced, the machine steels greatly exceed those of the structural type; together they comprise the most important class of metallic engineering material (after plain carbon steel).

The earliest efforts to improve the properties of steel simply consisted of increasing the carbon, manganese and silicon content. This made the steel stronger but simultaneously decreased its ductility. The first alloy steels contained single additions of nickel and chromium. They combined adequate strength with superior ductility and toughness, and were used principally for making armor plate and in bridge construction.

WHAT IS LOW-ALLOY STEEL?

Alloy steels, in general, are referred to by name for a particular application or in terms of composition. To eliminate any possible confusion, low-alloy steel is any steel with less than 5% nonferrous elements.

MICROSTRUCTURE

Steel properties and versatility are intimately related to microstructure; the element, iron, undergoes an allotropic transformation (that is, it changes from one crystal pattern to another). Control over transformation characteristics is gained by varying the steel's composition and its heat treatment. (These statements apply equally to carbon steels and low-alloy steels.)

In practice, both carbon steels and low-alloy steels are accorded identical heat treatments; however, actual temperatures may differ somewhat. Both give rise to identical microconstituents (insofar as can be judged by the naked eye). Chief distinctions lie, rather, in the nature of the constituents, as reflected in mechanical and physical properties of nonheat-treated low-alloy steels, and in the relative ease with which low-alloy steels can be through-hardened to produce optimum properties.

ALLOYING ELEMENTS' ROLE

Probably the most important effects of alloying elements in steel are 1) the rate of austenite transformation and 2) the depth of hardening. These two are by no means the only effects of practical significance. For example, the carbon steels contain small but highly significant quantities of sulphur, phosphorus, manganese and silicon. Manganese renders sulphur less harmful, thereby preventing hot shortness (rupture of hot steel during rolling or other mechanical working). Silicon, a strong degasifier, promotes steel soundness by removing oxygen. The sulphur and phosphorus are present as impurities, but phosphorus plays an important role in low-alloy, high-strength structural steels, while sulphur may be deliberately increased (with a simultaneous increase in manganese) to improve machinability.

ALLOYING ELEMENTS' EFFECTS

Alloying elements, in moderate amounts, do not alter the iron-carbon phase diagram's general appearance. But they do raise (or lower) critical temperatures, and shift phase boundaries appreciably.

Small amounts of certain elements may have significant effects upon steel properties (the relationship between manganese and sulphur was noted as an example). Another important effect of alloying elements has to do with steel deoxidation and grain refinement. Elements, in their order of decreasing effectiveness, used to abet this effect include:

Aluminum.
Silicon.

Zirconium.
Vanadium.
Titanium.
Chromium.

When used as deoxidizers, these elements appear as oxide inclusions in the steel. These elements tend to inhibit grain growth and cause shallow hardening. In addition, the carbides of vanadium and titanium promote small grain size: their carbides act as nuclei during the decomposition of austenite, which occurs because these carbides are quite stable at high temperatures. In those cases in which nitrogen may be detrimental to the steel, added titanium removes it.

ANNEALED AND NORMALIZED STEELS

Alloying elements slow down the rate of austenite transformation. And, as noted, they reduce carbon content of a eutectoid. These two factors combine to increase the volume of eutectoid, thereby producing a stronger matrix. Because such steel has more carbides in a stronger matrix, it has a higher strength than plain carbon steel.

Also, as strength is increased, both ductility and toughness are increased; the actions of the various alloying elements are rather unique in this effect, however, and cannot be generalized. The effect of an alloying element on a particular steel depends upon the treatment accorded that steel.

ALLOYING EFFECT ON TEMPERING

Tempering refers to the process of reheating a hardened steel to a temperature below the critical. In general, hardness decreases while toughness increases with increasing tempering temperature. Alloying elements tend to slow down the softening process. For a given tempering temperature, greater stress relief and higher hardness are possible for alloys than for plain carbon steel.

Toughness (impact strength) varies with tempering temperature, and certain anomalies should be noted. For example, during tempering, an effect noted mainly in conjunction with the alloy steels is brittleness, which occurs when steels are tempered at an elevated temperature. Referred to as "temper brittleness," it is not noted in alloy steels when the tempering temperature exceeds 1100°F.

ALLOYING ELEMENTS' EFFECT ON MARTENSITE TEMPERATURE

An important reference (for any steel to be hardened by quenching) is that temperature (M_s) at which austenite starts to transform to martensite. The principal factor affecting M_s is the steel's composition, with grain size and quenching temperature playing minor roles.

ALLOY ELEMENTS' EFFECT ON AUSTENITE RETENTION

"Retained austenite" refers to that portion of the original austenite that remains untransformed after heat treatment. In a low-carbon alloy steel, the amount of retained austenite varies somewhere between 0 and 10%, depending on the composition of the steel, the M_s temperature and the quenching procedure used; in high-carbon alloy steels the amount may be up to 80%.

The slower the quench (used in the following order: water, oil, air), the greater the retained austenite. If quenching is stopped at room temperature, and the end of the martensitic transformation (M_f) happens to fall below room temperature, some of the austenite has no opportunity to transform. Partial transformation to martensite (or a retardation of the cooling process) acts to stabilize austenite against further transformation. Reasons for trying to avoid retained austenite include:

It contributes to dimensional instability.

It may transform to martensite at room temperature, and cause cracking.

It reduces hardness and strength of the quenched specimen.

It may transform when subjected to tensile stress.

Products that form when austenite is tempered may reduce impact strength.

HEAT TREATMENT

"Heat treatment" means heating and cooling a metal or alloy in the solid state for the purpose of obtaining desirable conditions or properties. The nature of the events controlling the desired conditions or properties are not well known, and the many variations of form, shape, mass and design of the parts treated introduce heat transfer and temperature variations. Only appropriate compensating procedures, based on extensive experience and sound judgment, produce practical and successful results.

Heat treating ranges from such operations as the extreme hardening of tools to the strengthening and toughening of structural members, and includes homogenizing and softening of heavy castings and forgings, final conditioning of minute watch hairsprings, special treating of parts to permit fine surface finishing, relieving of residual stresses due to cold work or welding operations, surface hardening treatments, and malleabilizing of brittle castings.

Major purposes of heat treatment include:

To homogenize, by diffusing the alloying elements to attain uniformity of composition.

To soften, by modifying microconstituents to favor slip-plane formation.

To stress relieve, by permitting relaxation of stress.

To harden, by modifying microstructure to provide slip interference.

To toughen, by modifying microstructure to develop a degree of interference consistent with some slip before failure.

To add chemical elements from the surface, by absorption under favorable elevated temperature conditions.

To remove chemical elements from the surface, by heat expulsion or chemical extraction at higher temperatures.

To these major items can be added several less significant ones, such as improving resistance to corrosion, coloring, improvement of magnetic or electrical properties and establishment of desired prestress patterns.

The purposes outlined are fulfilled by the following general heat-treating processes.

ANNEALING

Annealing consists of softening treatments or procedures generally related to hardness reduction. It is carried out by heating the material and holding it at an elevated temperature and then cooling the material at a suitable rate. The annealing process enables atoms to migrate from positions where they are "squeezed-in" in between other atoms within the crystalline lattice structure to available vacant positions within the crystal as shown in Figure 15-4-5.

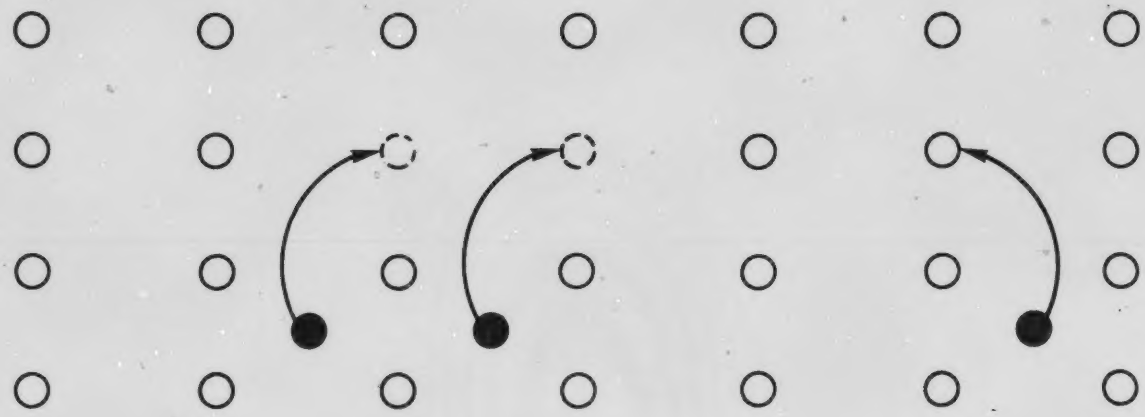


Figure 15-4-5 The Annealing Process

The homogenizing anneal of steel requires heating to temperatures considerably above the critical range for extended periods to permit uniform diffusion of chemical elements that undergo segregation upon initial solidification. The "soaking-pit" treatment of ingots is typical of this process. Iron and steel castings may be similarly treated for development of uniform physical properties where this is of sufficient importance.

Full annealing requires heating and holding the steel at a temperature above the critical range (until uniformity of temperature has been attained), followed by slow cooling. Heavy parts are usually cooled in the furnace, but lighter parts are sometimes removed and quickly buried in lime or other insulating media to control the cooling rate. Full annealing softens the steel and leaves it practically free from stresses. Alloy steels (less than 0.60% carbon) are generally easily machined in this condition.

Normalizing, although not part of the annealing process, is part of the associated procedure. Steel is heated to a temperature above the upper critical temperature and, after reaching uniformity, is removed from the furnace and allowed to cool in still air, which imparts physical properties intermediate between the annealed and the hardened conditions. Since it serves to relieve stress, as well as refine the grain, normalizing is commonly used to condition steel for subsequent heat-treatment tempering.

Cyclic (isothermal) annealing is similar to full annealing, except that the steel is removed from the furnace and quickly transferred to a salt bath or to another furnace (usually held at a temperature 100 to 200°F below the lower critical temperature until complete transformation to the desired annealed structure and hardness occurs). In this type of annealing, long furnace-cooling cycles - up to 30 hours - may be completed within 4 to 8 hours. Also, hot forgings may be taken directly from the press and cycle annealed, saving additional hours of processing.

TEMPERING

Tempering consists of reheating hardened steel to a temperature below critical to permit a degree of stress relief and to restore ductility. As this tempering temperature is increased, ductility increases and hardness decreases. Tempering temperatures may range from 212°F to about 1200°F. For maximum toughness, the "blue-brittle" range (450° to 750°F) should be avoided.

Martempering of steel consists of quenching from the austenitizing temperature into hot oil or molten salt at a temperature in the upper part of (or slightly above) the martensite range. This part is held in the quenching medium until its temperature throughout is substantially uniform. Then it is cooled (usually in air) at a moderate rate, to prevent any great difference in temperature between the surfaces and the center of the section.

Austempering is accomplished by heating the steel above the upper critical point and quenching into a molten-salt bath above the M_s point. The steel is held at this temperature long enough to equalize the temperature within the part and for the transformation product, bainite, to form completely. (Unlike martensite, obtained in martempering, bainite requires no additional tempering.) The part is air cooled from the molten-salt bath.

FIELD RESISTANCE HEATING

Resistance heaters, using heavy-gage wire in sintered-alumina insulating beads, are used to heat steel to relieve stress and preheat welds. Power is supplied by low-voltage welding transformers (on main power ac voltage) through an 80/20-nickel core wire.

The ability of a resistance alloy to resist oxidation depends on the formation of a stable tenacious oxide film. This film denies the oxygen access to the underlying metal surface. Wire life depends on a number of factors, including the amount of oxide film on the wire, gage of wire, superficial rating manner of support, frequency of control switching and degree of ease with which heat can be emitted.

ENGINEERING DATA FOR FIELD RESISTANCE HEATING CALCULATIONS

The kW in a heating element may be calculated as follows:

$$\text{kW} = \text{amps} \times \text{volts.} \qquad \text{Equation 15-4-1}$$

(Equation = Eq.)

The formula for calculating the kW required to heat a specific pipe joint or girth weld, in most cases, may be written as follows:

$$\text{kW/hour} = \frac{\text{outside diam. of pipe} \times \text{pipewall thickness} \times \pi \times \text{area to be heated} \times \rho \times \text{specific heat of pipe material} \times \text{soak temperature}}{3412\ \text{Btu/kW} \times \text{heat loss factor}}$$

where

ρ = 0.29
= weight in pounds of one cubic inch of steel.
0.12 = specific heat of pipe material.
3412 = Btu/kW.
0.50 = heat loss factor.

In a typical field resistance heating arrangement (Figure 15-4-6), finger elements are wrapped around the outside of a pipe in close proximity to the field weld to be stress relieved.

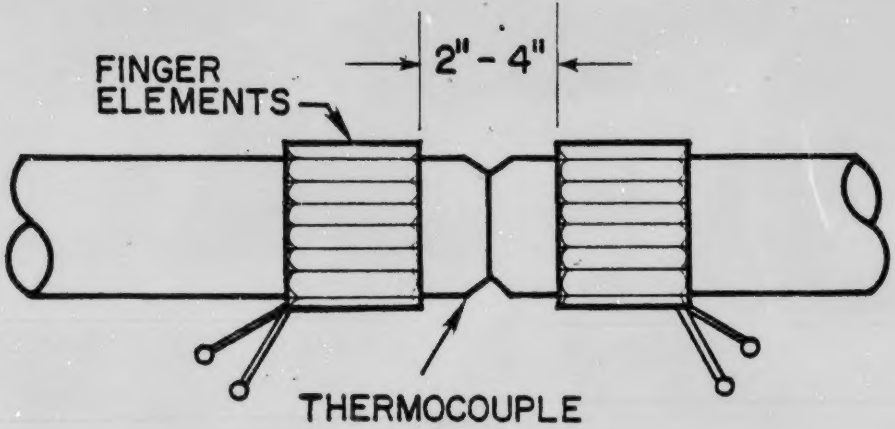

2" - 4"
FINGER ELEMENTS
THERMOCOUPLE

Figure 15-4-6. Typical field resistance heating arrangement.

EXERCISES

None.

MATERIALS

1 bar of low-carbon AISI 1010 steel.
1 bar of high-carbon AISI 1045 steel.

1 carbon steel pipe with drain stem of at least 16 inches.
Heating elements.
5 samples of low-carbon steel.
5 samples of medium-carbon steel.
5 samples of high-carbon steel.
5 samples of cast iron.
5 samples of alloy steel.
Hammer and center punch.
Vise.

PROCEDURES

1. Prepare two bars for a Jominy test, one from a low-carbon AISI 1010 steel and the other from a high-carbon AISI 1045 steel. Follow the procedure described in this module: take the necessary hardness readings to prepare 1) a depth hardness curve and 2) a Jominy curve for each material.
2. Select a suitable piece of carbon steel pipe with a drain stem of at least 16 inches; make necessary calculations to raise temperature of pipe to 1044°F; wrap pipe with heating elements (as calculated) and place two thermocouples on pipe O.D.; (use necessary safety precautions); raise temperature of pipe by providing calculated voltage and amperage; measure actual pipe-wall temperature.
3. Use five coded samples, one each of low-carbon steel, medium-carbon steel, high-carbon steel, cast iron and

alloy steel; heat treat each as follows:

Full anneal.
Normalize.
Temper.
Martemper.
No heat treatment - control.

4. Use a hammer and center punch to indent each sample (use the same striking force every time). Softer samples should give largest indentions. Which sample(s) are softer? Which would you have expected to be softer? Obtain code from instructor to identify heat treatment each received.
5. Put one end of each sample in a vise; try to bend the other end 90 degrees. Which samples were stronger? Which would you have expected to be stronger?
6. From your experiments, what can you generally conclude about heat treating?

DATA TABLE

To be provided by student.

REFERENCE MATERIALS

Johnson, C.G. and Weeks, W.R. *Metallurgy*. Chicago: American Technical Society, 1977.

Simons, E.N. *An Outline of Metallurgy*. New York: Hart Publishing Company, 1969.

TEST

Read each question carefully. Be sure your responses provide the specific information each question requires. Your answers should be brief.

1. Why might it be desirable to harden steel to a martensite structure?

2. What is meant by the hardenability of a steel?

3. How does cooling rate affect the formation of martensite?

4. What is meant by the term "critical cooling rate" of a steel?

5. What is the effect of a steel's carbon content, up to and beyond eutectoid composition, on its hardenability?

6. What is the effect of the austenite grain size on a steel's hardenability?

7. Answer these questions about the Jominy end-quench test:

   a. What is the purpose of the Jominy test?

   b. Why do the standards or specifications on the Jominy plot for any given steel take the form of a band, rather than a single line?

c. How (for what purpose) would the results of the Jominy test be used?

____

8. What is low alloy steel?

____

9. What effect do alloying elements have on the rate of austenite transformation?

____

____

10. When used as deoxidizer, what effect do alloys have on the depth of hardening?

____

____

11. What effect do the most commonly used alloys have on grain size? Why do they have this effect?

____

____

12. What is tempering? Why is tempering done?

____

____

13. What (if any) effect does tempering temperature have on ductility and hardness?

____

____

14. If stress and hardness of an alloy steel and a plain carbon steel were compared at a given tempering temperature, what would the results be?

____

____

____

15. What is "retained austenite"? Would low carbon alloy steels or high carbon alloy steels be likely to have the greatest amount of retained austenite?

____

____

16. What is one reason steel workers try to avoid retained austenite?

____

____

17. Define the term "heat treatment".

____

18. Name two major purposes of heat treatment. Explain how heat treating affects the steel in order to accomplish these two purposes.

a. ______________________________

____

b. ______________________________

____

19. What are the two main effects on steel of full annealing?

a. ______________________________

b. ______________________________

20. Briefly describe the normalizing of steel. What effect(s) does normalizing have?

____

____

____

21. Briefly described how either martempering or austempering is done?

____

____

22. What is the transformation product of martempering? What is the transformation product of austempering?

____

____

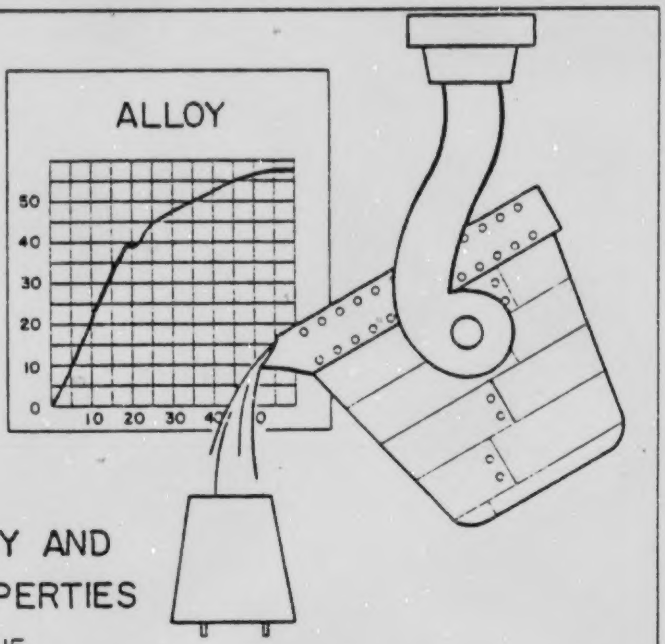
23. What are the two purposes of field resistance heating?

a. ______________________________

b. ______________________________

NUCLEAR TECHNOLOGY

MODULE 15-5 METALLOGRAPHIC EXAMINATION


ALLOY
50
40
30
20
10
0
10
20
30
40

METALLURGY AND
METALS PROPERTIES
COURSE 15

COURSE MODULES

COURSE 15 METALLURGY AND METALS PROPERTIES

MODULE 15-1	Fabrication Processes for Metals
MODULE 15-2	Chemical Analysis of Metals
MODULE 15-3	Basic Metallurgical Concepts
MODULE 15-4	Properties of Steel
⇨ MODULE 15-5	Metallographic Examination
MODULE 15-6	Mechanical Testing - Tensile, Bend, Hardness
MODULE 15-7	Mechanical Testing - Impact, Nick Break, Fatigue
MODULE 15-8	Failure Mechanisms in Metals

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INTRODUCTION

Metallographic examination provides a scientific determination of the structures of metals and alloys; the tools of metallography are the unaided eye and the optical reflecting microscope.

To observe the grain structures of metals, the processes of preparation of test specimens are presented. Also, the importance of good lab procedures is discussed. Because competence in specimen preparation only comes with practice, several procedures are included to provide this experience.

MODULE PREREQUISITES

The student should have completed the four previous modules in this Course.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Prepare metallographic specimens for examination.
2. Analyze specimens to determine their base metals, impurities and/or alloys; also, determine metal-working

and heat-treating processes afforded each specimen.

3. Given published photomicrographs, identify (by comparison) each specimen prepared.

PREPARATION OF METAL SPECIMENS

To observe the grain structure of a metal, an optically flat, mirrorlike surface must first be polished on a sample. Surface preparation is of great importance, because variations in technique may distort or exaggerate essential parts of the structure. Polishing for observations requires attainment of a mirrorlike surface by cutting away normal irregularities (as opposed to causing high areas to flow into low areas, as in buffing metal). Flow, which distorts a surface, may lead to erroneous conclusions about structure characteristics.

CONVENTIONAL POLISHING

The first stages of cutting a surface to a flat plane are usually accomplished by grinding with successively finer grades of abrasive powders (cemented onto papers). The direction of cutting is altered at each change to a finer abrasive; this change of direction facilitates recognition of the stage at which coarser (deeper) scratches are replaced by more shallow ones (Figure 15-5-1).

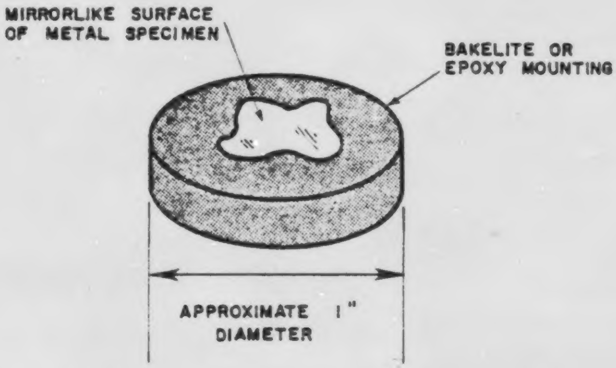

MIRRORLIKE SURFACE OF METAL SPECIMEN
BAKELITE OR EPOXY MOUNTING
APPROXIMATE 1" DIAMETER

Figure 15-5-1. Metallurgical test specimen.

Micrographs (Figure 15-5-2) show the surfaces of speci-

After No. 0 emery paper.

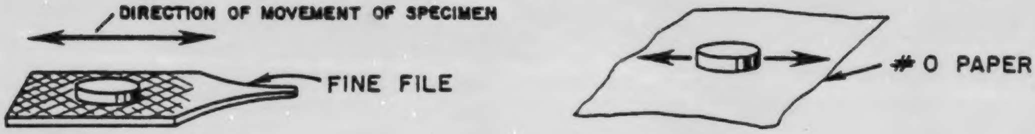
After No. 00 emery paper.

After No. 000 emery paper.

After polishing on broadcloth with levigated alumina and etching with a solution of ammonium hydroxide and hydrogen peroxide.

Figure 15-5-2. Cast brass (50X magnification) at different stages of polishing.

mens at magnification 50X after grinding. Finer abrasives than No. 000 cannot be mounted onto paper. Also, this grade may not be uniform, and final approximation to a mirror surface must be obtained by other means. Usually, a rotating disk, covered with a special cloth charged with abrasive particles, is used. Two different disks may be used: one with a relatively coarse abrasive and, later, another with finer particles (Figure 15-5-3).


DIRECTION OF MOVEMENT OF SPECIMEN
FINE FILE
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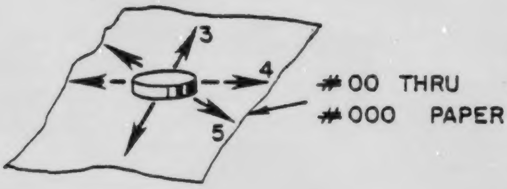
STAGE 1

STAGE 2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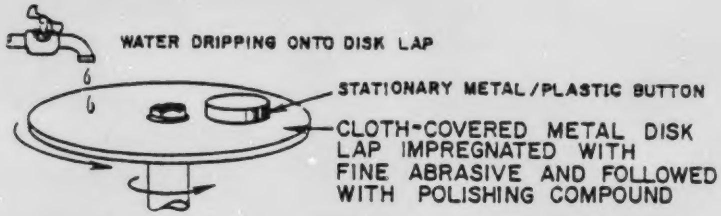
STAGES 3 THROUGH 5


WATER DRIPPING ONTO DISK LAP
STATIONARY METAL/PLASTIC BUTTON
CLOTH-COVERED METAL DISK LAP IMPREGNATED WITH FINE ABRASIVE AND FOLLOWED WITH POLISHING COMPOUND

STAGES 6 AND 7

Figure 15-5-3. Stages of specimen preparation.

Polishing results may be affected by coarse dust particles settling from the air onto the fine papers or cloth laps. Also, coarse particles on the specimen may be carried to the next finer paper or lap.

Chemical changes may affect some abrasives (e.g., fine magnesium oxide, used as a final polishing agent, may pick up carbon dioxide from the air or water to form coarse particles of magnesium carbonate, which mar the surface.

Pressure used by the individual holding the specimen on the cutting papers or laps influences results. Too little pressure retards the rate of polishing and leads to pits in the final surface; too much pressure causes local overheating and severe distortion to an appreciable depth. The correct degree of pressure varies for different metals and can be learned only by actual polishing (and repolishing).

ELECTROLYTIC POLISHING

Among the alternative procedures that can be used to prepare metallographic specimens, electropolishing deserves special mention. (Practically complete freedom from distortion and other extraneous effects is possible by this method.)

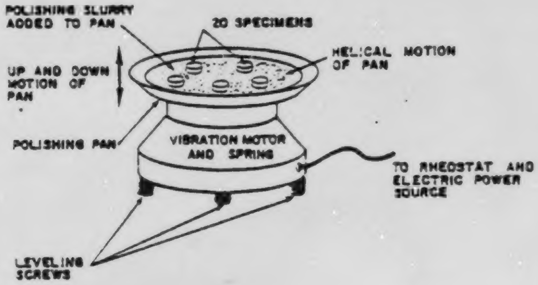
Electrolytic polishing of metal specimens is accomplished by controlled anodic corrosion in an electrolyte. Procedures, involving optimum composition, optimum temperature, current density, voltage and time are described in appropriate manufacturers' literature, research papers and the American Society for Testing Materials (ASTM) Standards.

Electrolytic polishing can save considerable time and labor, but its chief advantage is the absence of surface distortion. It is therefore particularly valuable in polishing soft metals, such as pure aluminum, zinc or other metals whose structures are particularly subject to smearing by distortion (e.g., stainless steels). The method is commercially employed to replace buffing where the shape of a part makes buffing difficult.

VIBRATORY POLISHERS

A recent innovation, vibratory polishing, is achieved by use of a shallow metallic polishing bowl attached, by means of leaf springs, to a base (Figure 15-5-4). Application of a pulsed current (from a transformer in the base) causes the polishing bowl to move in a helical pattern. The horizontal component of the helical motion causes the metallographic mount to move around the circumference of the polishing bowl. The vertical component literally pulls the polishing bowl down, away from the sample on the half cycle so that, on completion of the cycle, the sample recontacts the bowl at a new location. The polishing bowl

Figure 15-5-4.
Vibratory polishing machine.


POLISHING SLURRY ADDED TO PAN
20 SPECIMENS
HELICAL MOTION OF PAN
UP AND DOWN MOTION OF PAN
POLISHING PAN
VIBRATION MOTOR AND SPRING
TO RHEOSTAT AND ELECTRIC POWER SOURCE
LEVELING SCREWS

is usually 12 inches or more in diameter and permits the clamping of any standard metallographic polishing cloths to its flat surface. Also, polishing abrasive, in the form of a slurry, can be added to a depth of 1/16 to 1/8 inch. Plastic-mounted samples may then be inserted into stainless steel holder weights (weighing 300 to 400 g) and placed face down on the polishing bowl surface. By means of a rheostat, helical motion amplitude (of the polishing dish) is controlled so that the samples slowly rotate around the outer periphery of the polishing bowl.

The vibratory polisher can be used for rough, intermediate and final polishing; each step takes from 15 to 30 minutes. Because as many as 20 samples can be polished at one time, it is at least as efficient as other methods of polishing large groups of samples.

Vibratory polishing requires much less manipulative skill than the usual metallographic polishing. It takes less of the metallographer's time (once samples are placed on polisher, other duties may be performed until the cycle is complete). Yet another advantage is that the samples can be examined individually at any time during the polishing cycle without stopping the polisher or the polishing of other samples.

ETCHING SURFACES

After polishing, the specimen surface must be etched to bring out details of metal structure. The chemical (etching solution) differentially attacks parts of the metallic surface to reveal structural condition.

If the specimen is to be studied by eye only, or at magnifications of less than 25 diameters (microscopic examination), usually it is etched deeply to increase contrast in appearance of sections attacked at different rates. (Magnifications of more than 25 diameters are called "micrographs.")

If magnification is in the range of 50 to 100 diameters, the specimen is usually given a moderately deep etch to obtain contrast. Very fine structures, to be magnified 500 to 1000 times, require only a relatively light etch.

The appearance of the final polished (but unetched) specimen (Figure 15-5-2) is not reproduced because its uniform surface reveals no structural details. Fairly deep etching (with a mixture of ammonia and hydrogen peroxide) reveals a coherent group of polygonal areas shaded somewhat differently. (Note: Each area represents a crystal grain whose axes are at different angles with respect to its neighbors and the overall surface.) This particular etching solution attacks different crystal faces at different rates, thus tending to outline specific crystal faces.

A crystal in which an outlined face is parallel to the surface of polish has a maximum flatness and, consequently, reflectivity for light, which causes it to have a bright appearance. If, in a different crystal, the outlined face is tilted away from the polished surface, that grain has a roughened or saw-tooth type of surface that does not fully reflect light to the observer's eye. Such crystals appear dark, to varying degrees, depending on the extent of etching and the actual angle of the outlined faces to the surface.

Not all etching solutions have this effect of "darkening" crystals of differing orientations. In Figure 15-5-2, many lines, inclined slightly from the horizontal, actually are scratches covered by flow during the final polishing and then revealed by the etch. (The etch removed much of the distorted surface layer.) The lines are identified as scratches because they cross crystalline grain boundaries with no change in direction.

TRANSPARENT MATERIAL SPECIMENS

In a study of grain structure in transparent materials, reflected-light (metallurgical) microscopes are not used (Figure 15-5-5). Instead, thin sections (about 0.03-mm thick)

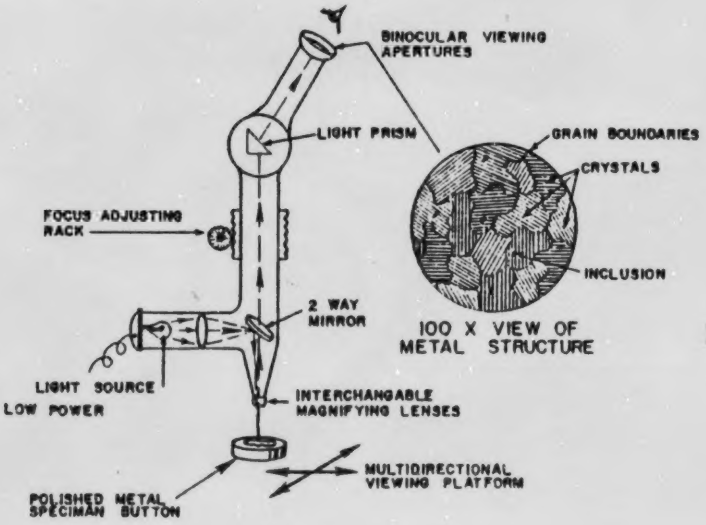

BINOCULAR VIEWING APERTURES
LIGHT PRISM
GRAIN BOUNDARIES
CRYSTALS
FOCUS ADJUSTING RACK
INCLUSION
2 WAY MIRROR
100 X VIEW OF METAL STRUCTURE
LIGHT SOURCE
LOW POWER
INTERCHANGABLE MAGNIFYING LENSES
MULTIDIRECTIONAL VIEWING PLATFORM
POLISHED METAL SPECIMAN BUTTON

Figure 15-5-5. Reflected-light metallurgical microscope.

with flat, parallel sides are prepared by sawing the specimen with a diamond saw. Then they are polished. Finally, cemented to a glass slide and placed on the stage of a petrographic (polarizing) microscope, these specimens are examined with polarized transmitted light.

Because many transparent minerals have different indices of refraction for light traveling in different directions, the individual mineral grains appear colored. Etching, used to distinguish between metal grains, is, therefore, an unnecessary step in the examination of transparent materials.

The microstructure of those minerals that are not transparent can be studied with reflected, polarized light; an ore microscope is used. And, again, individual grains are revealed by their different colors.

EXERCISES

1. Find, in the library, books and other references with photomicrographs of the following metals:
   - Gray cast iron.
   - Malleable cast iron.
   - White cast iron.
   - Copper.
   - Brass or bronze.
   - Aluminum.
   - Low-carbon steel (both cold-worked and annealed).
   - High-carbon steel (both cold-worked and annealed).

Sketch each photograph; identify grains; note impurities present; state heat-treating process, if any.

2. Use Reference Materials list; from these or other references, explain the effect of grain size in iron and steel on the following properties:
   - Tensile strength.
   - Ductility.
   - Hardness.
   - Corrosion resistance.
   - Machinability.
3. List at least eight things that affect grain size in iron and steel; state whether each is good or bad and tell why.

MATERIALS

3 metal specimens (e.g., copper, brass, iron or aluminum).

Different amounts of primary alloy (e.g., low-carbon steel, high-carbon steel).

Materials for metal working and heat treating (e.g., cold-working, annealing).

Plastic molder for metal specimen preparation.

1 inch x 6 inch file (flat/fine).

Miscellaneous emery papers (grades No. 0 through 000).

Polishing laps.

Various polishes (cerium oxide, tin oxide).

Vibratory polishing machine.

Metal specimen etchants.
Reflecting light metallurgical microscope.

PROCEDURES

METALLOGRAPHIC SPECIMENS

Obtain three metal specimens from instructor. (Specimens should be different base materials - e.g., copper, brass, iron, aluminum - different amounts of primary alloy - e.g., low-carbon steel, high-carbon steel - and different types of metal-working and heat-treating - e.g., cold working, annealing.)

1. Mount specimens, as demonstrated by instructor.
2. Polish specimens, as described in this module, until approved by instructor.
3. Observe specimens through a reflected-light microscope.
4. Sketch specimen surfaces.
5. Etch specimen surfaces.
6. Again, observe and sketch specimen surfaces.
7. Explain improvements made by etching.
8. With aid of photomicrographs (provided by instructor, or from reference books), identify the three specimens in Data Table 15-5-1 (fill in all blank spaces).

DATA TABLE

DATA TABLE 15-5-1

Properties	Specimen 1	Specimen 2	Specimen 3
Base Metal			
Impurities and Alloys Present			
Type of Metal Working			
Type of Heat Treatment			
Comments			

REFERENCE MATERIALS

Barrett, Charles S. and Massolski, T.B. Metallography. New York: McGraw-Hill, 1966.

Gifkins, R.C. Optical Microscopy of Metals. New York: American Publishing Co., 1970.

Johnson, C.G. and Weeks, W.R. Metallurgy. Chicago: American Technical Society, 1977.

Ormandy, P.C. An Introduction to Metallurgical Laboratory Techniques. New York: Pergamon Press, 1968.

TEST

Read each question carefully. Provide the specific information each question requires. Be brief. If you need more space, write on the backs of the test sheets.

1. What is the essential difference between polishing metal and buffing it? Would you polish or buff metal to prepare metal specimens for examination? Why?

2. List three factors that can significantly affect the results of conventional polishing of the metallurgical test specimen.

   a.

   b.

   c.

3. In conventional polishing, why is a successively finer abrasive needed to grind the metal's surface to a flat plane?

4. Why is electrolytic polishing used to polish soft metals, such as zinc or pure aluminum?

5. What is one advantage of vibratory polishing over conventional polishing?

6. In preparing metal specimens, what is the purpose of the etchant?

7. What is a micrograph?

8. Compare the study of the grain structure of transparent minerals and non-transparent metals by very briefly describing these aspects of study: (a) the instruments used to view the grain structure (b) the means of making the crystals visible (c) the general appearance of the crystals that makes it possible to distinguish them.

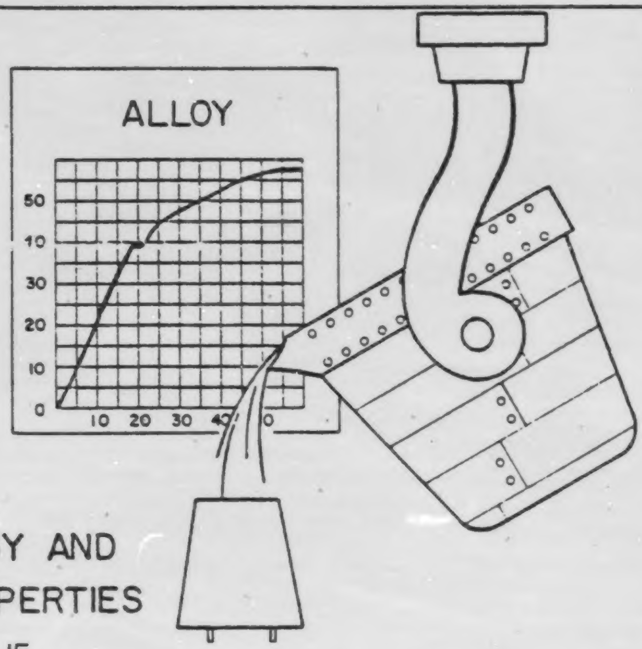
Instruments:

Means of making crystals visible:

General Appearance of crystals:

NUCLEAR TECHNOLOGY

MODULE 15-6 MECHANICAL TESTING - TENSILE, BEND, HARDNESS


ALLOY
50
40
30
20
10
0
10
20
30
40

METALLURGY AND
METALS PROPERTIES
COURSE 15

COURSE MODULES

COURSE 15 METALLURGY AND METALS PROPERTIES

	MODULE 15-1	Fabrication Processes for Metals
	MODULE 15-2	Chemical Analysis of Metals
	MODULE 15-3	Basic Metallurgical Concepts
	MODULE 15-4	Properties of Steel
	MODULE 15-5	Metallographic Examination
⇨	MODULE 15-6	Mechanical Testing - Tensile, Bend, Hardness
	MODULE 15-7	Mechanical Testing - Impact, Nick Break, Fatigue
	MODULE 15-8	Failure Mechanisms in Metals

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INTRODUCTION

Metals owe their importance to their unique mechanical properties, the combination of high strength with the ability to change shape plastically (ductility and a malleability). This plasticity enables them to be shaped into such items as automobile bodies, tin cans and girders, by processes of mechanical working such as pressing, drawing, forging and rolling. Even more important, this same plasticity gives strong metals their extraordinary toughness, which is the ability to endure all of the knocks and shocks of long rough service without breaking or crumbling away.

Therefore, the mechanical properties of a material determine its response to a particular type of load or stress. To study the mechanical properties of materials, forces are applied to test specimens and the resulting deformations are measured.

This module discusses three such tests:

Tensile.
Bend.
Hardness.

Also, basic principles of operation, actual operating procedures and evaluations of test results, as these items relate to the three tests, are covered.

MODULE PREREQUISITES

The student should have completed Modules 15-1, "Fabrication Processes for Metals," 15-3, "Basic Metallurgical Concepts," 15-4, "Properties of Steel," and 15-5, "Metallographic Examination."

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Perform the following mechanical tests:
    - Tensile strength.
    - Yield strength.
    - Hardness.
2. Given tensile strength, yield strength and hardness, test values of various materials; compare them with values published in the American Society for Testing Materials (ASTM) Specifications and Standards for the same materials.
3. Given the necessary sketches, describe two types of bend tests and discuss advantages of each.
4. Discuss affects of tensile strength and hardness on machinability of ferrous material.
5. Anneal and normalize low-, medium- and high-carbon steels; perform mechanical test on each; report hardness, tensile strength, yield strength and ultimate tensile strength.

Strength is the ability of a material to resist deformation. A number of strength values must be known to fully understand the overall strength characteristics of a metal, including:

Tensile strength.
Compressive strength.
Fatigue strength.
Yield strength.

TENSILE STRENGTH

Tensile strength is defined as the maximum load in tension that a material withstands prior to failure. This most commonly given strength is stated in pounds force per square inch of cross-sectional area (lbf/in^2, psi).

TENSILE TEST MACHINE

Tensile strength is measured in a tensile testing machine (Figure 15-6-1). The machine, which applies a slowly increasing pull to the ends of a test piece until the material actually breaks, consists essentially of two components:

A device for pulling specimen apart.
A means of measuring required pulling force.

[If elongation or stretching of the specimen undergoing

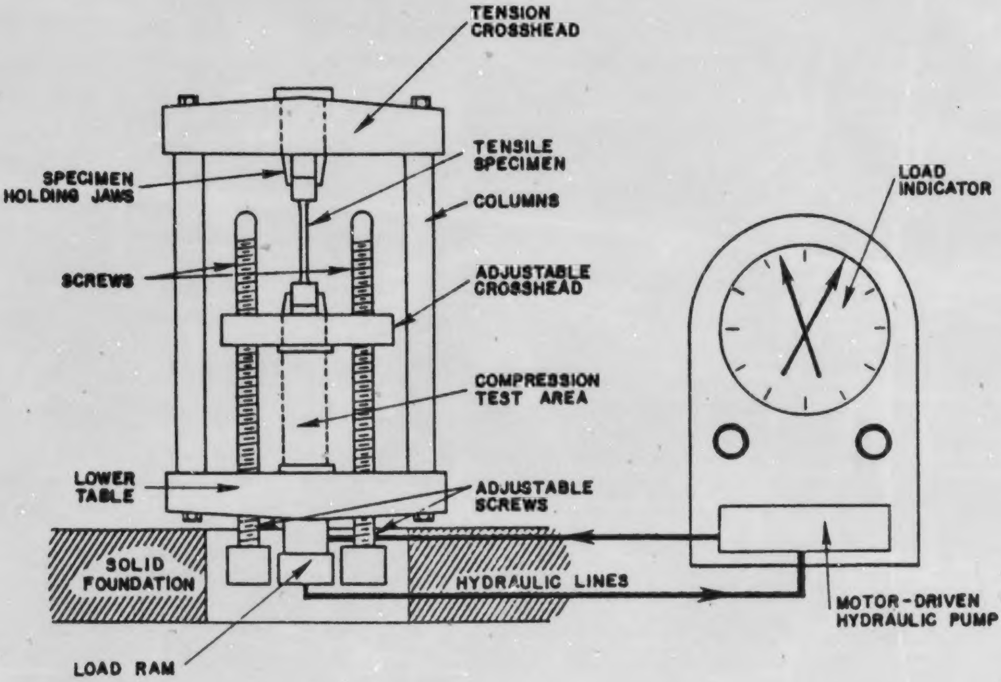

TENSION CROSSHEAD
TENSILE SPECIMEN
SPECIMEN HOLDING JAWS
COLUMNS
SCREWS
ADJUSTABLE CROSSHEAD
COMPRESSION TEST AREA
LOWER TABLE
ADJUSTABLE SCREWS
SOLID FOUNDATION
HYDRAULIC LINES
LOAD RAM
LOAD INDICATOR
MOTOR-DRIVEN HYDRAULIC PUMP

Figure 15-6-1. Tensile testing machine.

tests is to be measured, a third device (an extensometer) is necessary - Figure 15-6-2.]

The tension crosshead of the tensile testing machine and the lower table are bolted firmly together by means of rigid columns, and the lower table is connected to the hydraulically operated load ram (piston). An adjustable (vertically), crosshead, mounted on screw columns, can be hydraulically turned to raise or lower crosshead to satisfy specimen length.

Connected to the load ram is a hydraulic system, which includes an electrically operated pressure pump and load indicator.

Before the tensile specimen is placed into the testing machine, two or four small prick marks are made in the parallel

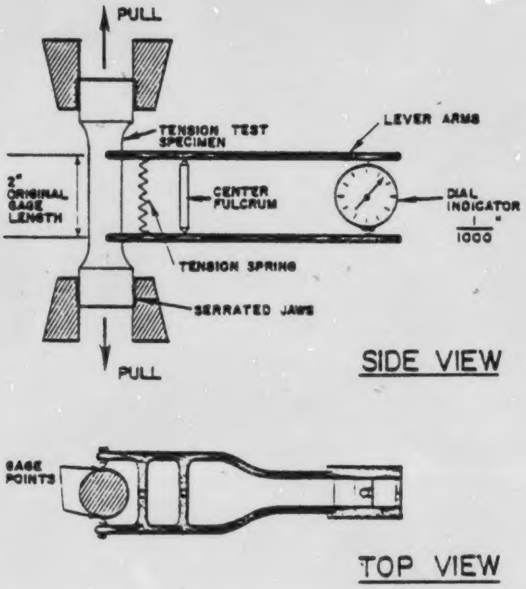

PULL
TENSION TEST SPECIMEN
LEVER ARMS
2" ORIGINAL GAGE LENGTH
CENTER FULCRUM
DIAL INDICATOR
1/1000"
TENSION SPRING
SERRATED JAWS
PULL
SIDE VIEW
GAGE POINTS
TOP VIEW

Figure 15-6-2. Mechanical extensometer.

test portion (over the standard gage length) to locate the extensometer (Figure 15-6-3).

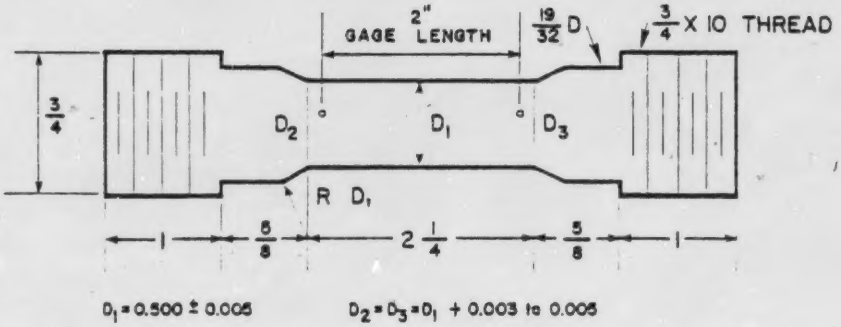

2" GAGE LENGTH
19/32 D
3/4 X 10 THREAD
3/4
D2
D1
D3
R D1
1
5/8
2 1/4
5/8
1
D1 = 0.500 ± 0.005
D2 = D3 = D1 + 0.003 to 0.005

Figure 15-6-3. Typical ASTM tensile test specimen.

The test is conducted at room temperature. Slowly and steadily, a tensile load is applied to a test specimen. The machined specimen is placed in the upper and lower wedge-type jaws of the machine, with the vertical axis of the specimen situated symmetrically. The adjustable crosshead is lowered to provide a minimum of tension.

When the specimen is properly situated and the jaws are snug and accurately aligned vertically, the extensometer is attached to the test specimen. As the test proceeds, the load on the specimen is shown by the pointer on the load indicator scale, and the change in length of the specimen is read from the extensometer dial indicator. The specimen will show a noticeable necking down - thinning in the center portion (Figure 15-6-4) - indicating the approaching break-point of the specimen.

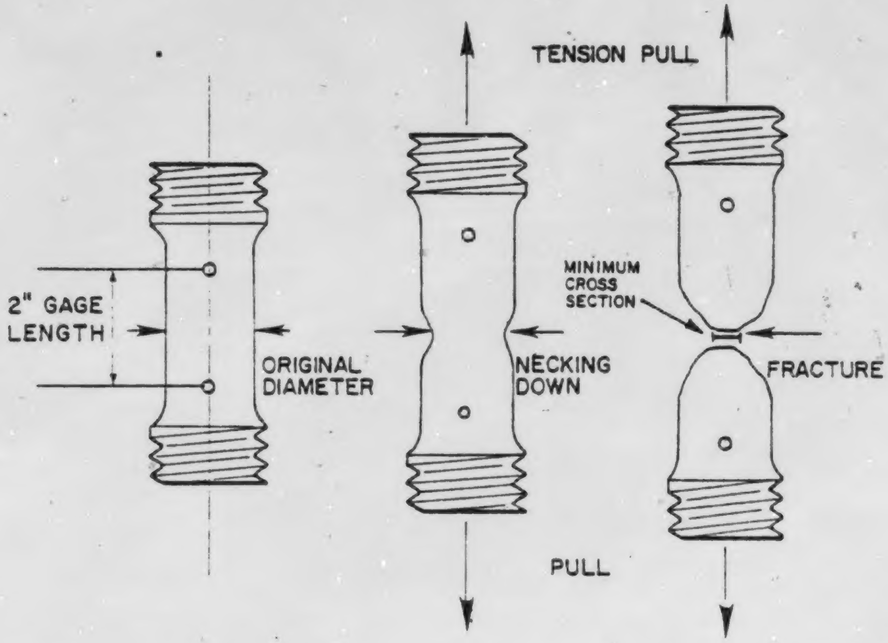


Figure 15-6-4. Indicating appearance of test specimen during tensile testing.

Accurate reading of both load and length changes simultaneously requires two technicians: the one at the load indicator records load readings while the other is at the dial indicator to record the extension readings of the test specimen.

Most tensile testing machines have a "rider pointer" that moves along with the recording pointer so that, when the test specimen breaks, the recording pointer goes back to zero and leaves the rider at the correct load reading. In any event, care should be taken to accurately obtain the load at which the test specimen fractures.

Another factor reported is that of reduction in area, obtained from fractured portions of test specimen, by measuring minimum cross-sectional area at fracture and using the following equation:

$$\text{Reduction in area (\%)} = \frac{A_o - A_f}{A_o} \times 100\%$$

Equation 15-6-1
(Equation = Eq.)

where

A_o = original cross-sectional area of specimen used.

A_f = final cross-sectional area of specimen.

It is imperative in calculating percent elongation that the original gage length be reported, since percent elongation will vary according to original gage length.

STRESS-STRAIN CURVES

The first step after testing is to convert the actual load and elongation data into stress-strain information by using the following equations:

$$\text{Stress} = \frac{\text{load}}{\text{area}}, \text{ psi} \qquad \text{Eq. 15-6-2}$$

where

Load = incremental readings taken during test, pounds.
Area = specimen cross-sectional area based on original diameter, square inches.

Note: Rupture stress is based on rupture load divided by fracture cross-sectional area:

$$\text{Strain} = \frac{\text{change in length}}{\text{original gage length}} = \frac{\text{ins}}{\text{ins}}.$$

Change in length is the incremental readings (taken during test) from the extensometer dial gage (original gage length is usually two inches).

In a typical stress-strain diagram for a ductile material such as soft steel (Figure 15-6-3), a number of important properties derived from a tensile test may be plotted on such a diagram:

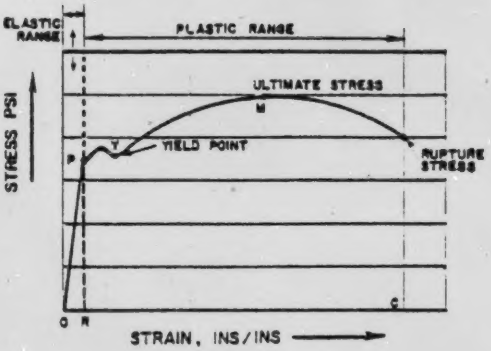


Figure 15-6-5.
Typical stress-strain diagram for ductile material (with yield point).

Yield Point. As load increases on test specimen, a stress is reached at which material, without an increase in load, continues to deform. Stress at point Y (Figure 15-6-5) is referred to as "yield point." At times, upper and lower yield points may appear - stress actually decreases momentarily. Yield points of metals are of major importance; design of structural members in machines, towers, beams, and so on are based largely on the yield strengths.

Proportional and Elastic Limits. Sometimes used as a measure of yield point, "proportional limit" is defined as the stress at which a stress-strain curve first shows a measurable deviation from linearity; "elastic limit" is the maximum stress to which a metal may be subjected without permanent plastic deformation. The difficulty with using these quantities is that they depend entirely on sensitivity of the test equipment and cannot be expected to be reproducible. Also, an elastic limit can be found only by repeated loading and unloading of the specimen, a tedious procedure at best. Yield point is a much more useful property, and use of the terms elastic limit and proportional limit should be discouraged.

Tensile Strength (ultimate stress or strength). The maximum load sustained by a specimen during tensile test, when divided by its original cross-sectional area (sometimes called "ultimate strength"), tends to be an arbitrary quantity.

This is because the value of stress is not divided by the reduced area which results from the sustained load being applied.

True Breaking Strength (rupture stress or strength). This quantity is the load on the specimen at the time of fracture, divided by the cross-sectional area at the fracture. It is, therefore, a purely physical quantity.

Tensile Elongation. This measurement is frequently taken as an indicator of the ductility of a material under tensile test. It is determined, not from the load-elongation curve, but rather from examination of the failed specimen:

$$\text{Elongation } (\%) = \frac{L_f - L_o}{L_o} \qquad \text{Eq. 15-6-3}$$

where

L_f = final gage length.

L_o = original gage length, usually 2 inches.

Young's Modulus. This measurement, defined as tensile stress divided by tensile strain for elastic deformation, is represented by the slope of the linear part of the stress-strain curve.

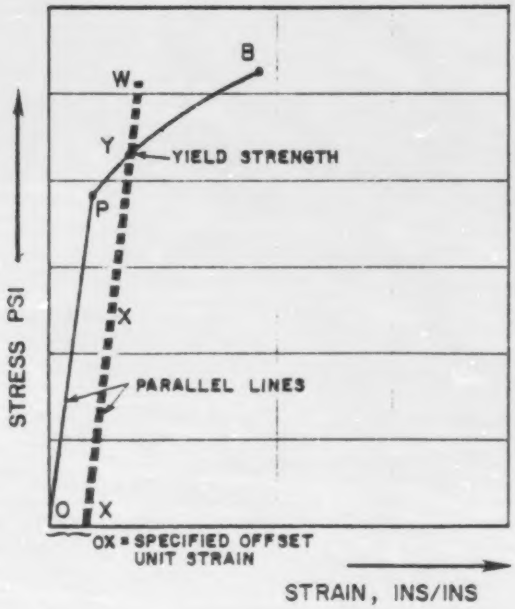
Yield Strength. When a material under tension reaches the limit of its elastic strain and begins to flow plastically, it is said to have yielded. Yield strength is the stress at which plastic flow commences. Some materials, under certain well defined test conditions, show a sharp yield point on their stress-strain curves (Figure 15-6-5). In most cases, however, a gradual transformation occurs.

In the case of many nonferrous materials and high-carbon alloy steels, which do not have definite yield points, the most useful determination that can be made is yield strength (the stress at which a material is permanently elongated a specified small amount). At this yield point, the curve begins to deviate from a straight line (i.e., stress is no longer directly proportional).

On the diagram (Figure 15-6-6), the specified "offset" OX extends along the strain axis. This offset is commonly valued at 0.15 to 0.20 percent of gage length. From this point, a line (dotted) is drawn parallel to the original line of the stress-strain diagram (line XW is drawn parallel to line OP), and the intersection of XW with the stress-strain diagram is located (point Y). Yield strength of the material equals the stress at point Y.

Note: Material strain shown in Figure 15-6-5 is much larger than that shown in Figure 15-6-6 (both have same scales). The former is "ductile" (it exhibits much plastic deformation before breaking); the latter is "brittle" (it deforms plastically very little before breaking).

Figure 15-6-6.
Typical stress-strain diagram illustrating yield strength.



BEND TESTS

Bend testing, an important requirement of mechanical testing, discloses ductility (the ability to be deformed), especially in the testing of welds. Two types of bend tests are used:

Guided bend tests.
Free bend tests.

Guided Bend Tests

In a guided bend test, a section of "as welded" seam is prepared to approximate dimensions (Figure 15-6-7). The

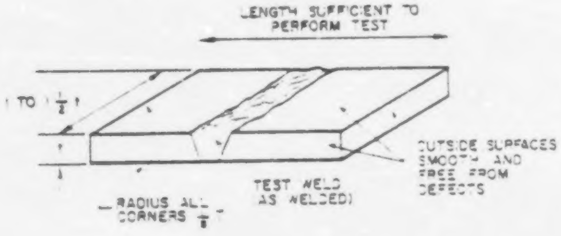

LENGTH SUFFICIENT TO PERFORM TEST
1 TO 1 $\frac{1}{2}$"
OUTSIDE SURFACES SMOOTH AND FREE FROM DEFECTS
TEST WELD (AS WELDED)
RADIUS ALL CORNERS $\frac{1}{8}$"

Figure 15-6-7.
Preparation of "as welded" seam test specimen.

section is placed into a loading device, then bent about a rod (at the test weld) to a specified number of degrees. After bending, it should not evidence surface cracks (Figure 15-6-8).

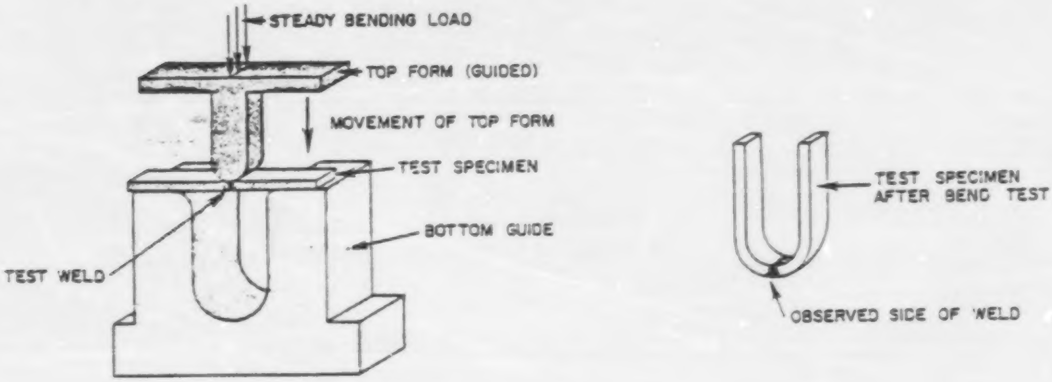

STEADY BENDING LOAD
TOP FORM (GUIDED)
MOVEMENT OF TOP FORM
TEST SPECIMEN
BOTTOM GUIDE
TEST WELD
TEST SPECIMEN AFTER BEND TEST
OBSERVED SIDE OF WELD

Figure 15-6-8. Guided bend test setup (and completed test specimen).

Free Bend Tests

In a free bend test, the specimen is placed between the upper and lower platens of a tensile testing machine (or similar device that can apply a heavy, steady load). This test determines the relative ductility of metal that is to be formed, usually sheet, strip plate or wire and for determining the soundness or toughness of metal. The jaws are closed until the required bend is produced (Figure 15-6-9). The specimen is usually bent over a specified diameter through a specified angle for a specified number of cycles. Gage marks on specimen are compared before and after testing to arrive at percentage elongation (use Equation 15-6-3).

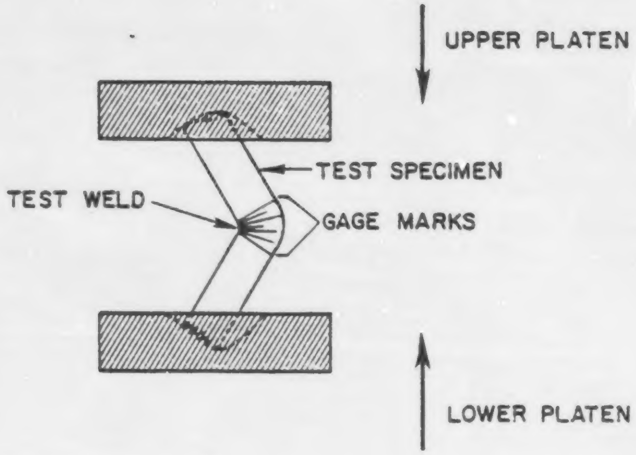


Figure 15-6-9.
Free bend test setup.

HARDNESS

Hardness of a material may be defined as the property that resists penetration. It is measured by a hardness tester. Hardness is not a true physical property, rather it consists of a combination of properties; therefore, it is revealed by a comparative test.

There are a number of methods of measuring hardness, and each measures a different combination of properties. Consequently, hardness as measured by one test is not necessarily comparable with hardness as measured by another, although formulas are given for rough conversions.

The principal hardness tests include:

File (scratch).
Rebound.
Penetration.

In the file test, resistance of the material to scratching is determined by comparison with a set of standard files of known hardness; this test is useful and simple.

The rebound test is less empirical: the height of rebound of a diamond-tipped hammer dropped from a given height onto the test piece is observed and compared; the harder the material, the greater the rebound. What is being measured, in this case, is the amount of energy absorbed in the material during impact. The rebound test enjoys little use in modern practice.

The most common way of measuring hardness is to determine resistance to the penetration of a nondeformable ball or cone. Three types of penetration hardness testers are discussed below.

BRINELL HARDNESS

In this test a vertical, hand-operated or electrically-operated, hydraulic press forces an accurately hardened and ground steel ball into the specimen to be tested. The ball has a diameter of 10 mm ± 0.0025 mm, and it is under a load of 3000 kg for ferrous metals, such as iron or steel, or 500 kg for nonferrous metals such as copper or brass (Figure 15-6-10).

The tester is designed to press the steel ball, under proper load, for a period of at least 10 seconds for ferrous metals and 30 seconds for nonferrous metals. Diameter of the impression created is automatically measured by the tester, giving a value suitable for most applications; however, if greater precision is required, a micrometer-slide, comparator-type Brinell microscope is used - it measures to ± 0.01 mm diameter.

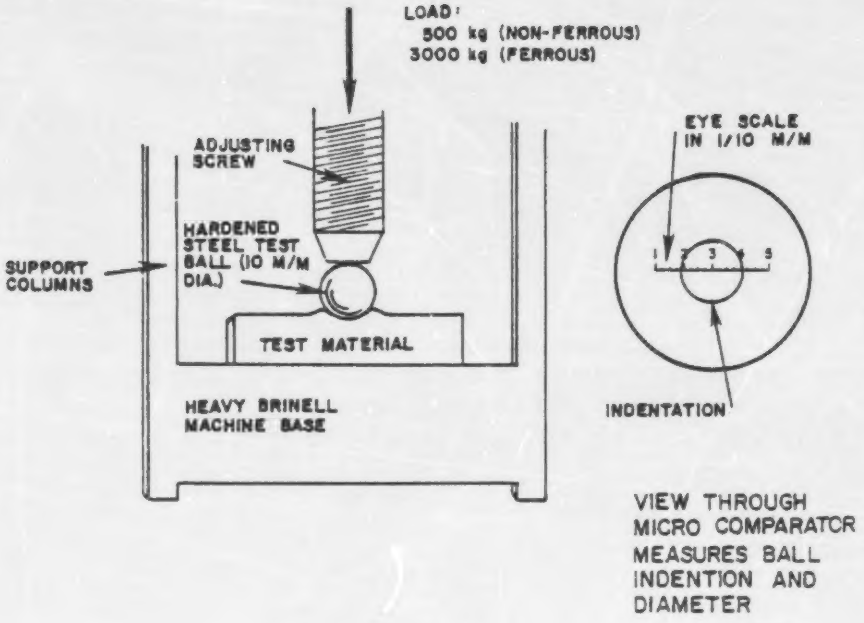

LOAD:
500 kg (NON-FERROUS)
3000 kg (FERROUS)
ADJUSTING SCREW
HARDENED STEEL TEST BALL (10 M/M DIA.)
SUPPORT COLUMNS
TEST MATERIAL
HEAVY BRINELL MACHINE BASE
EYE SCALE IN 1/10 M/M
1 2 3 4 5
INDENTATION
VIEW THROUGH MICRO COMPARATOR MEASURES BALL INDENTION AND DIAMETER

Figure 15-6-10. Brinell test and indentation measurement device.

The Brinell hardness number (Bhn) is actually the ratio of load (in kilograms) to area of the impression (in millimeters):

$$\text{Bhn} = \frac{P}{\frac{\pi D}{2}\left(D - \sqrt{D^2 - d^2}\right)} \quad \text{Eq. 15-6-4}$$

where

P = test load, kg.

D = test ball diameter, mm.

d = diameter of impression, mm.

Tensile strength can be generally related to hardness; for example, the tensile strength of heat-treated carbon steel and low-alloy steel may be estimated by multiplying Bhn by 500. (This conversion should be used with caution: it is a useful ballpark rule but can be misleading for unusual materials or heat treatments.)

ROCKWELL HARDNESS

Rockwell hardness testing is the most widely used method for determining hardness. There are several reasons for this distinction: (a) the Rockwell test is simple to perform and it does not require highly skilled operators; (b) by use of different loads or indenters, Rockwell hardness testing can be used for determining hardness of most metals and alloys, ranging from the safest bearing materials to the hardest steels; (c) a reading can be taken in a matter of seconds with conventional manual operation and even in less time with automated setups; and (d) no optical measurements are required because all readings are direct readings.

Rockwell hardness testing differs from Brinell hardness testing in that the hardness is determined by the depth of indentation made by a constant load impressed upon an indenter. Although a number of different indenters for Rockwell hardness testing, the most common type is a diamond ground to a 120°F core with a spherical apex having a 0.2 mm radius, which is known as a Brale indenter as shown in Figure 15-6-11.

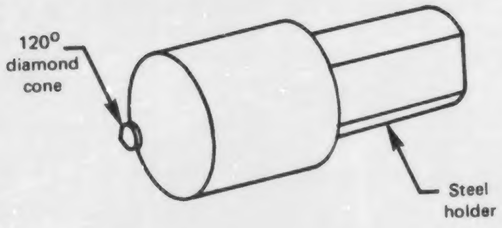
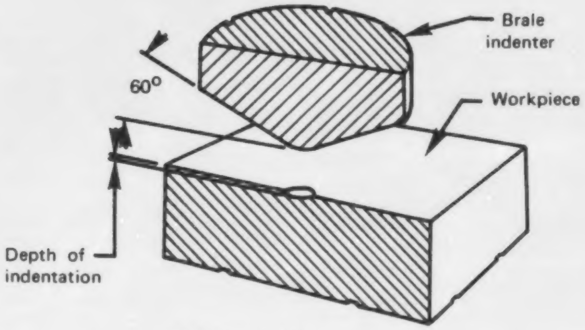


Figure 15-6-11 Diamond-Cone Brale Indenter used in Rockwell Hardness Testing Shown at Twice the Normal Size. (Courtesy of Metals Handbook, 8th Edition, Volume 11.)

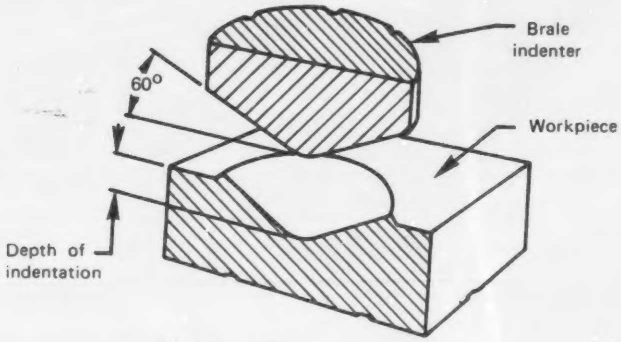
The Rockwell hardness test consists of measuring additional depth to which an indenter is forced by a heavy (major) load shown in Figure 15-6-12(b) beyond the depth of a previously applied light (minor) load as shown in Figure 15-6-12(a).

The minor load is applied to the workpiece as shown in Figure 15-6-12(a) first, and a reference or "set" position is established on the dial gage of the Rockwell hardness tester. Then the major load is applied as shown in Figure 15-6-12(b). Without moving the workpiece, the major load is then removed and a Rockwell hardness number is automatically indicated on the dial gage. The entire operation takes only about 5 to 10 seconds. Hence, this testing technique is not only a simple one but a quick one as well.

This reading is based on the depth of indentation, less the elastic recovery following removal of the major load, less penetration caused by the minor load. A high number indicates a shallow impression (a hard material), and a low number indicates a deep impression (a soft material).


Brale indenter
60°
Workpiece
Depth of indentation

(a) Minor load


Brale indenter
60°
Workpiece
Depth of indentation

(b) Major load

Figure 15-6-12 Indentation on a workpiece made by application of (a) the minor load and (b) the major load by a diamond Brale indenter in Rockwell Hardness Testing.

The hardness value is based on the difference in depths of indentation produced by the minor and major loads. (Courtesy of Metals Handbook, 8th Edition, Volume 11)

Diamond indenters are used mainly for testing material such as hardened steels, whereas steel ball indenters are used for testing such materials as soft steel, copper alloys, and aluminum alloys.

There are two basic types of Rockwell hardness testers, regular and superficial. Both of these operate on similar basic mechanical principles and have similar features. Figure 15-6-13 shows a schematic view of a regular Rockwell hardness tester. Superficial testers are similarly constructed.

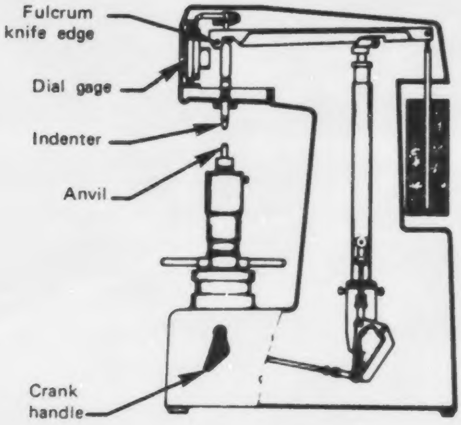


Figure 15-6-13 Sketch of a Regular (Normal) Rockwell Hardness Tester (Courtesy of Metals Handbook, 8th Edition, Volume 11.)

The Rockwell hardness tester may also be used for testing specimens of various sizes and shapes. The Rockwell hardness tester shown in Figure 15-6-13 is of standard design and can with various designs of anvils and adapters, accommodate a broad range of workpiece sizes and shapes.

For example, the hardness testing of long workpieces requires special fixtures as shown in Figure 15-6-4. This test setup uses an outboard vertical support as shown.

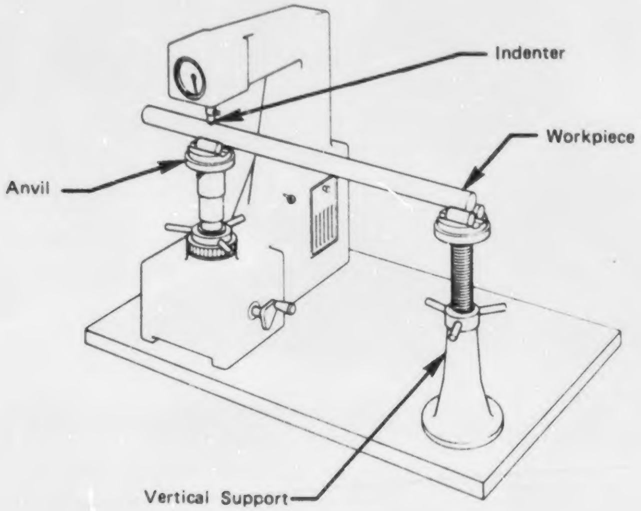


Figure 15-6-14 Rockwell Hardness Test Setup Using an Outboard Vertical Support for a Long Shaftlike Workpiece. (Courtesy of Metals Handbook, 8th Edition, Volume 11.)

The Rockwell hardness test may also be applied to inner surfaces of cylindrical workpieces by means of a special "gooseneck adapter" as shown in Figure 15-6-15.

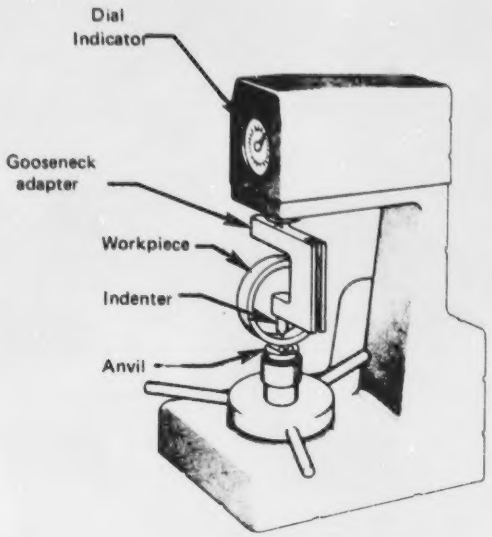


Figure 15-6-15 Setup for Rockwell Hardness Testing of Inner Surfaces of Cylindrical Workpieces Using a Gooseneck Adapter (Courtesy of Metals Handbook, 8th Edition, Volume 11.)

VICKERS HARDNESS

The Vickers hardness was introduced in England in 1925 by R. Smith ahd G. Sandland. The Vickers hardness test follows the Brinell principle, in that an indenter of definite shape is pressed into the material to be tested, the load removed, the diagonals of the resulting indentation measured and the hardness number calculated by dividing the load by the surface area of the indentation.

The Vickers hardness test uses a square-based, diamond-pyramid indenter with an included angle of 136° between opposite faces. Loads usually range from 5 to 100 kg.

In a Vickers machine, the specimen is elevated to within 1 mm of the indenter, and the lever-loading system is set in the starting position by means of a foot lever acting on a weight-and-cam mechanism, which produces motive power for the test. When the weight-and-cam mechanism is released, the indenter descends under load, indents the specimen and then returns to the starting position. Both the rate of descent and the time indenter remains in contact with the specimen are controlled by an oil dashpot (usually adjusted for a time cycle of from 10 to 20 seconds). The hardness number is derived from Equation 15-6-5:

$$Vhn = 1.854 \frac{P}{D^2} \qquad \text{Eq. 15-6-5}$$

where

P = load, kg.

D = diagonal length of square impression, mm.

The Vickers hardness test equipment is designed to apply the load without impact with friction effects reduced to a minimum.

Several types of hardness testers have proved acceptable for performing the Vickers test previously described. Figure 15-6-16 shows a typical Vickers hardness tester with its principal components.

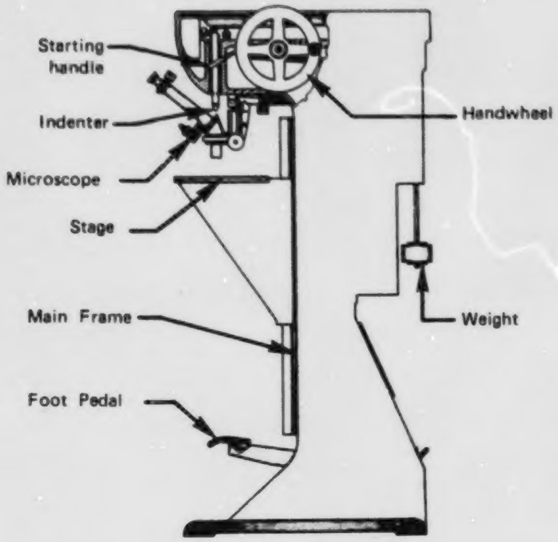

Starting handle
Indenter
Microscope
Stage
Main Frame
Foot Pedal
Handwheel
Weight

Figure 15-6-16(a) Vickers Hardness Tester (Courtesy of Metals Handbook, 8th Edition, Volume 11.)

SPECIAL PRECAUTIONS TO BE FOLLOWED IN HARDNESS TESTING

Be sure to calibrate machine with test blocks of known hardness before each test, or at satisfactory established intervals.

Specimen must be flat for best results; however, round specimens may be tested by using an anvil or stage made of two round parallel bars welded to a flat stage, so that round specimen lies in the space between parallel bars.

Specimen must be well supported.

Specimen must be thoroughly cleaned and free from scale, oxides, surface machine marks and inclusions. (Note: A machine-ground area gives the most accurate results.)

Specimen must be thick enough so that no bulge will show up on underside. Thickness usually must be at least ten times the depth of the impression to be made by indenter.

When using either a Rockwell or Brinell tester, the steel ball cannot test materials as hard as (or harder than itself). (Note: The Brinell test is inaccurate for hardness readings greater than about 450.)

Successive indentations should be spaced to avoid interference.

Tester must be mounted free from the effects of mechanical vibrations.

Care must be taken to avoid operating testing machine without a specimen in it: the penetrator might penetrate a hardened support surface, reducing its measuring capability.

NORMALIZING AND ANNEALING EFFECT ON MACHINING

Normalizing is a term referring to reheating of steel to about 100°F (40°C) above its critical temperature (temperature at which a change in crystal structure, phase or physical properties occurs for a given pressure and then cooling it in air. Two main purposes of normalizing include:

To refine grain size.

To obtain carbide size and distribution more favorable for carbide solution treatment.

As-rolled grain size depends upon finishing temperature during rolling operation, which is subject to wide variations and results in correspondingly wide variations in grain size. As the name implies, normalizing serves to ensure a uniform, relatively fine-grained microstructure.

Machining is made much easier and more effective by normalizing in a hypoeutectoid steel consisting substantially of ferrite and coarse pearlite; such a steel is easier to machine if the ferrite and cementite are more evenly and finely distributed. Steel, in the soft condition, is apt to tear in machining, but normalizing brings about a slight increase in hardness and, consequently, a more brittle chip, thereby improving machinability.

In as-rolled alloy steels, especially if they have been slow cooled after rolling, the carbides tend to be rather large in size; therefore, they become difficult to dissolve on later austenitizing treatments. In such cases, normalizing ensures a more uniform and a finer carbide particle size, facilitating subsequent heat treatment, and ensuring a more uniform final product.

ANNEALING

The term annealing refers to any heating and cooling operation associated with the softening of steel or iron. The main purposes of annealing are 1) to relieve cooling stresses induced by cold or hot working, and 2) to soften the steel to improve its ability to be more easily machined or formed. At times, it involves only a subcritical heating to relieve stresses, to recrystallize cold-worked material, or to spheroidize the carbides. In other instances, it may involve heating above the critical temperature, with subsequent transformation to pearlite (or directly to a spheroidized structure) when cooled.

EXERCISES

Use Table 15-6-1 (obtained as a result of tensile test-

TABLE 15-6-1

TENSILE TEST RESULTS FOR A STEEL SPECIMEN

Load (lbs)	Change in Length (ins)	Stress (lbs/sq in)	Strain (ins/ins)
1000	0.00042	5102	0.00021
2000	0.00080	10204	0.00040
4000	0.00150	20408	0.00075
6000	0.00220	30612	0.0011
8000	0.00300	40816	0.0015
9000	0.00320	45918	0.0016
9500	0.00350	48469	0.00175
9900	0.00375	50510	0.00187
10050	0.00422	51276	0.0021
10500	0.011	53571	0.005
11010	0.017	56173	0.008
12100	0.025	61735	0.012
13000	0.062	66326	0.031
14100	0.290	71939	0.145
11950	0.492 (break)	60969	0.246

ing a steel specimen); calculate 1) ultimate strength, 2) rupture strength and 3) yield strength; identify all significant points. (Note: Assume standard ASTM specimen with 2-inch test length.)

To calculate stress ($\frac{\text{load}}{\text{area}}$), the diameter of standard test specimen must be measured; therefore, assume

$d = 0.500$ in $= \frac{\pi}{4}(0.5)^2 = \frac{\pi}{4} \times 0.25$

area - 0.196 in^2.

When specimen broke, diameter was 0.249 in; therefore, area $= \frac{\pi}{4}(0.249)^2 = 0.063$ in^2; this area must be used to calculate rupture stress.

Stress for each load can now be calculated by dividing load by 0.196 in^2.

1. Calculate strain:

$$\text{Strain} = \frac{\text{change in length}}{\text{gage length}} = \frac{\text{change in length}}{2 \text{ in}}$$

2. Plot a stress-strain curve, with stress as vertical axis and strain as horizontal axis.
3. Locate line parallel to original plot, starting at 0.002-inch strain. The point at which it crosses graph is yield strength of material, which happens to be 56,000 lbs/in^2.
4. Ultimate tensile strength (T_u) is obtained by dividing maximum load carried by specimen during test, divided by original specimen cross-sectional area:

$$T_u = \frac{14100}{0.196} = 71{,}939 \text{ lbs/in}^2.$$

5. Rupture strength (R) is found by dividing load at instant of break by original cross-sectional area:

$$R = \frac{11950}{0.196} = 60{,}969 \text{ lbs/in}^2.$$

True rupture strength is equal to load at instant of rupture divided by final cross-sectional area:

$$R_t = \frac{11950}{0.063} = 186{,}682 \text{ lbs/in}^2.$$

"True" figure is considerably higher than calculated one, showing how material becomes stronger as it is worked to a reduced sectional area at time of break.

6. Plot an enlarged version of stress-strain diagram for strains up to 0.01 in/in. Starting at a strain of 0.002 in/in, draw a line parallel to curve and note that, where it crosses, curve is yield point; YP = 56,000 psi.
7. Draw a typical stress-strain curve of a ductile, ferrous material. Label axes and significant parts of curve.
8. A test specimen, 2" long and 1/2" in diameter, reached yield point when given a 700-pound force. Calculate stress and strain if elongation was 0.247 inch.
9. Sketch and explain principles of operation of a Brinell hardness tester.

MATERIALS

Tensile testing machine.
Brinell hardness testing machine.
Rockwell hardness testing machine.
Vickers hardness testing machine.
Visual indentation microscope.
Tensile test extensometer.
Fine point dividers.
Vernier calipers.
0 - 1 inch micrometer.
ASTM material sufficient to machine tensile test specimens in low-and high-carbon content.
Low-, medium- and high-carbon steel hardness specimens, approximately 2" x 2" x 1".
Center punch.
Graph paper sheets, graduated in tenths.

PROCEDURES

TENSILE TEST

1. Obtain from instructor standard ASTM tensile test specimens from low-, medium- and high-carbon steel.
2. Perform tensile test on each specimen; plot results on a stress-strain diagram (use Data Table 15-6-1). Identify:
    - Yield strength point.

Ultimate tensile stress point.

Breaking stress point.

3. Identify steel with highest yield strength; explain why it is highest.

HARDNESS TESTS

1. Obtain three specimens each of low-, medium- and high-carbon steel (for each carbon content, one specimen is to be in an as-purchased condition, one in an annealed condition and one in a normalized condition). Metal types are to be the same as used in the first procedure (above); in fact, the as-purchased specimens may be the same specimens.
2. Measure Brinell hardness, Rockwell hardness and Vickers hardness; record results on Data Table 15-6-2.
3. Compare test results with values (for same materials) taken from ASTM Handbook.
4. Do hardnesses agree with ASTM Handbook values? (Explain all answers on Data Table.)
5. What effect does heat treating have?
6. What would you predict yield and tensile strengths to be for heat-treated specimens?
7. Which carbon content(s) give highest hardness reading(s)? Explain why.
8. Which hardness tester is easiest to use? Which gives most accurate results?

DATA TABLE

DATA TABLE 15-6-1
LOW/MEDIUM/HIGH-CARBON STEEL TENSILE TEST

Measured		Calculated		
Load (lbs)	Change in Length (inches)	Stress (psi)	Strain (in/in)	Notes

	Measured Value	ASTM Handbook Value	% Difference
ASTM Steel Type			
Yield Strength (psi)			
Ultimate Tensile Strength (psi)			
Tensile Stress (psi)			
Elastic Modulus ($\frac{\text{psi}}{\text{in/in}}$)			
Slope of Line in Elastic Region			

DATA TABLE 15-6-2

HARDNESS TEST

	Brinell Hardness	Rockwell Hardness	Vickers Hardness	ASTM* Value	Comments
Low-Carbon Steel					
As-Purchased					
Annealed					
Normalized					
Medium-Carbon Steel					
As-Purchased					
Annealed					
Normalized					
High-Carbon Steel					
As-Purchased					
Annealed					
Normalized					

* Corresponds to ______________ Hardness Scale

REFERENCE MATERIALS

Dieter, G.E. Mechanical Metallurgy. New York: McGraw-Hill, 1961.

Johnson, C.G. and Weeks, W.R. Metallurgy. Chicago: American Technical Society, 1977.

Consult metallurgy or materials testing books available at your library.

Metals Handbook, 8th Edition, Volume 11, Nondestructive Inspection and Quality Control, American Society for Metals, 1976.

TEST

Read each question carefully. Provide the specific information each question requires. Be brief. If you need more space, write on the backs of the test sheets.

1. Define the term "strength" of a material:

2. Define tensile strength:

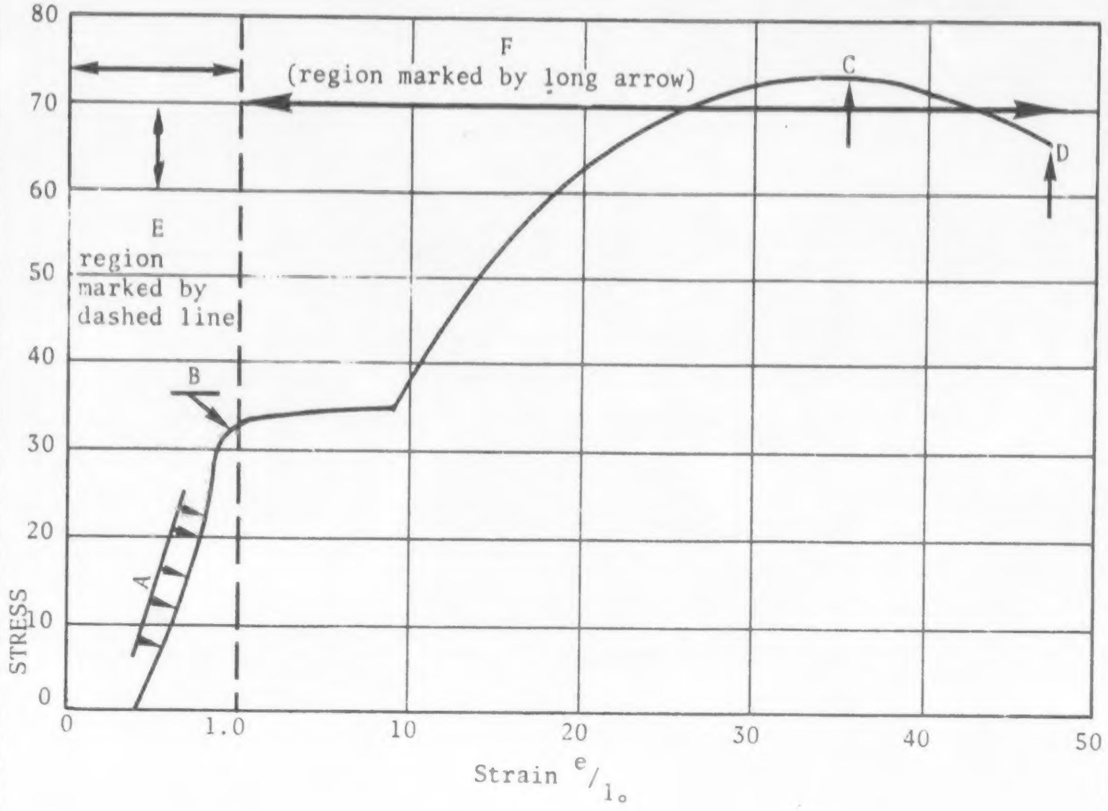
3. In tensile strength testing, what is the purpose of an extensometer?

4. In testing tensile strength, how do you know when the specimen's breaking point is being approached?

5. Define stress:

6. Define strain:

7. Write the name of the lettered (A-F) parts of the stress-strain graph below:



A ____________________

B ____________________

C ____________________

D ____________________

E ____________________

F ____________________

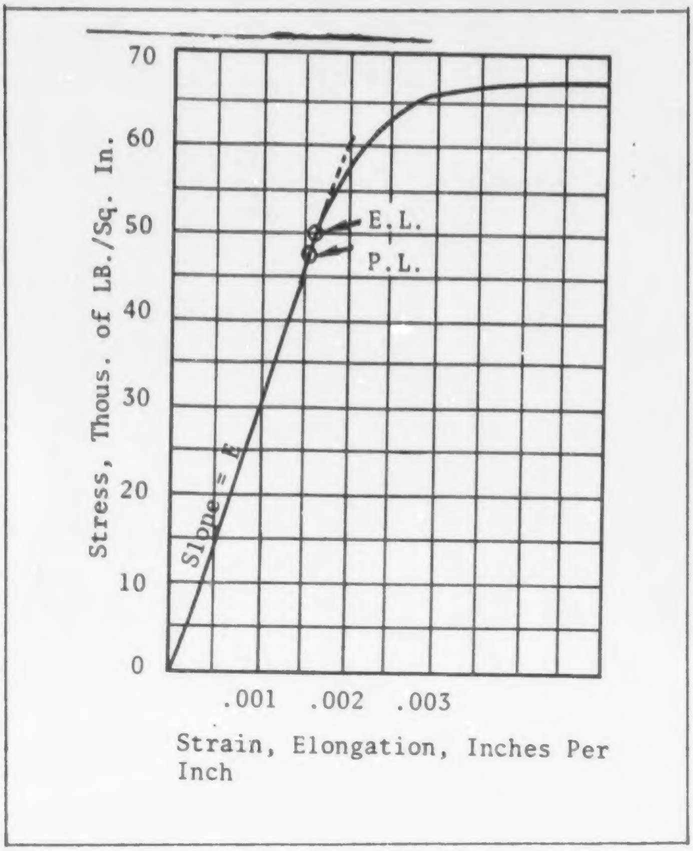
8. What part (region) of the stress-strain graph gives an indication of the metal's stiffness or elasticity?

9. How would you know when a metal had reached its yield point? (What happens at the yield point?)

10. How is the deformation that occurs beyond a metal's elastic limit different from the deformation that occurs at stresses below the elastic limit?

11. At stresses beyond the elastic limit, what difference would you expect in a metal with good ductility, as opposed to a metal with fair to poor ductility?

12. Determine yield strength by the "offset" method.



13. What is the main purpose of bend tests?

____

____

____

14. Name one type of bend test.

____

15. What is meant by the "hardness" of a metal?

____

____

____

16. What does a file test examine in order to determine metal's hardness? What measure of hardness does a penetration test use?

17. List two special precautions that should be followed in hardness testing:

a.

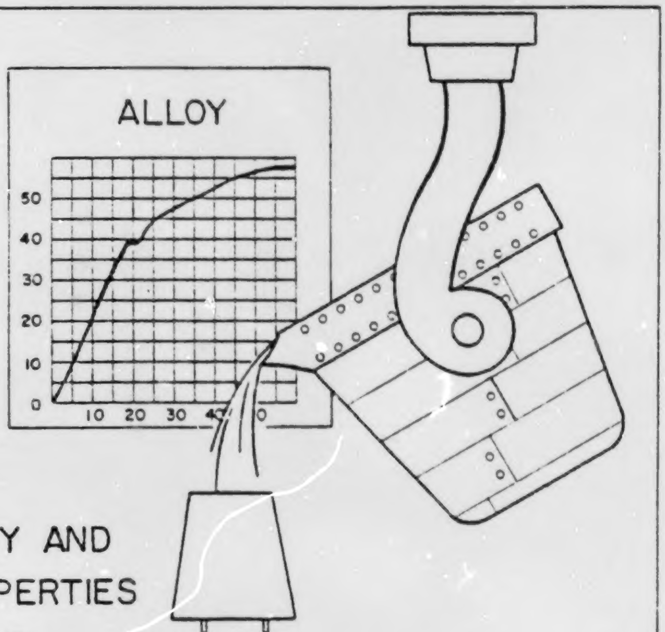
b.

18. What is the purpose of the Brinell, Vickers, and Rockwell testers?

19. Why does normalizing improve the machinability of hypoeutectoid steels?

NUCLEAR TECHNOLOGY

MODULE 15-7 MECHANICAL TESTING - IMPACT, NICK BREAK AND FATIGUE


ALLOY
50
40
30
20
10
0
10
20
30
40

METALLURGY AND
METALS PROPERTIES
COURSE 15

COURSE MODULES

COURSE 15 METALLURGY AND METALS PROPERTIES

MODULE 15-1	Fabrication Processes for Metals
MODULE 15-2	Chemical Analysis of Metals
MODULE 15-3	Basic Metallurgical Concepts
MODULE 15-4	Properties of Steel
MODULE 15-5	Metallographic Examination
MODULE 15-6	Mechanical Testing - Tensile, Bend, Hardness
MODULE 15-7	Mechanical Testing - Impact, Nick Break, Fatigue
MODULE 15-8	Failure Mechanisms in Metals

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INTRODUCTION

When a material is tested for mechanical properties under conditions requiring rapid load application, the procedure becomes an "impact test." In impact (dynamic) testing, a machined or surface-ground specimen is struck and broken by a single blow in a specially designed testing machine; it is the energy absorbed in breaking the specimen that is measured.

Energy values determined in this way are qualitative comparisons of selected specimens; and although frequently specified as acceptance criteria, such values cannot be converted into numbers suitable for engineering calculations.

Fatigue is the progressive localized permanent structural change which occurs in a material subjected to repeated or fluctuating strains at stresses having a maximum value less than the tensile strength of the material. Fatigue testing determines the ability of a material to withstand repeated applications of various types of stress.

Small stresses applied to a material which are insufficient to produce appreciable plastic deformation can still lead to fatigue. Situations of this type frequently occur in engineering practice. A common example is a rotating beam which loaded transversely to the axis of rotation, as in the case of an automobile axle. It is known that an axle loaded in this manner can fail due to fatigue.

Higher stresses can also cause a fatigue type of failure. For example, if the stresses are high enough for some small region of the metal to be minutely deformed, permanent damage begins to build up in that region.

Very high stresses, too, can be the ultimate cause for failure due to fatigue. For example, very high localized stresses caused by excessive vibration or load noise (sonic fatigue occurring in jet aircraft), or from local stress concentrations at notches, keyways, and so on.

MODULE PREREQUISITES

The student must have completed all previous modules in this Course.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Explain differences between Charpy, Izod, and Drop-weight impact tests.

2. Differentiate between tension and torque (as applied to solid and hollow cylinders).
3. Describe and explain the four essential parts of a fatigue-testing machine.
4. Explain what fatigue tests measure and identify the organization that sets up fatigue-test specifications.
5. Design a Charpy impact test bar, perform a Charpy impact test, and interpret the results.

IMPACT TESTS

Impact tests are made by applying a sudden load, or impulse, to a test specimen. The impulse is derived from a falling weight or, more commonly, from a swinging pendulum (Figure 15-7-1). What is usually measured is "energy absorbed" from the impulse required to break the specimen. The "tougher" the material, the greater the energy absorption. A brittle material, such as glass or fully hardened steel, may absorb virtually no energy upon breaking.

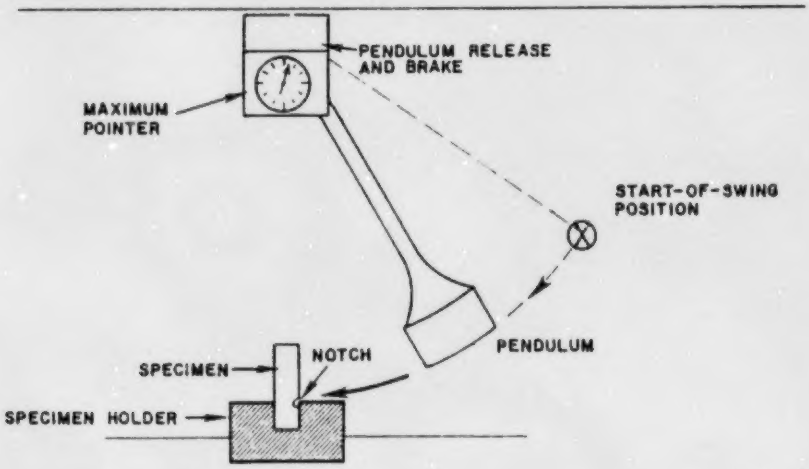

PENDULUM RELEASE AND BRAKE
MAXIMUM POINTER
START-OF-SWING POSITION
PENDULUM
NOTCH
SPECIMEN
SPECIMEN HOLDER

Figure 15-7-1. Impact testing machine.

Essential features of an impact test include:

Suitable specimen.

Anvil (support) on which test specimen is placed.

Moving mass of known kinetic energy (which must be great enough to break the test specimen).

Device for measuring residual energy in moving mass.

Three types of procedures may be typically used for impact testing: Charpy, Izod, and Drop-weight either of which, with a simple head adjustment, may be performed on one type of machine (Figure 15-7-1).

Data taken from a notch-bar test are subject to limited interpretation; that is, they merely indicate that a given steel is or is not brittle when tested at 1) a certain temperature with 2) a notch of a given form and 3) a measured severity of impact. Comparison of results (of one material with another) products a useful estimate of quality, and it allows a correlation of properties with properties of other materials of presumably similar composition.

CHARPY TEST

The Charpy test specimen is supported at both ends in the machine as a simple beam (Figure 15-7-2). The specimen

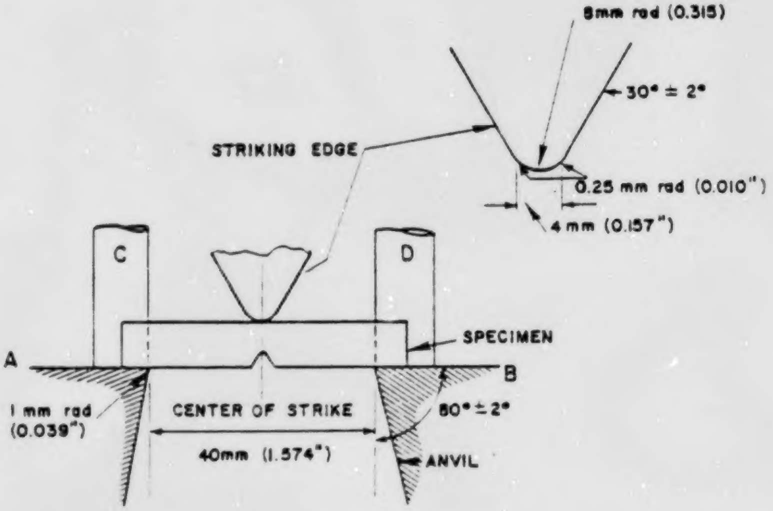
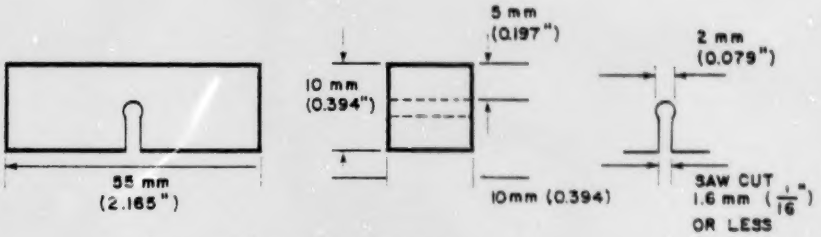

8mm rad (0.315)
30° ± 2°
STRIKING EDGE
0.25 mm rad (0.010")
4 mm (0.157")
C
D
SPECIMEN
A
B
1 mm rad (0.039")
CENTER OF STRIKE
80° ± 2°
40mm (1.574")
ANVIL

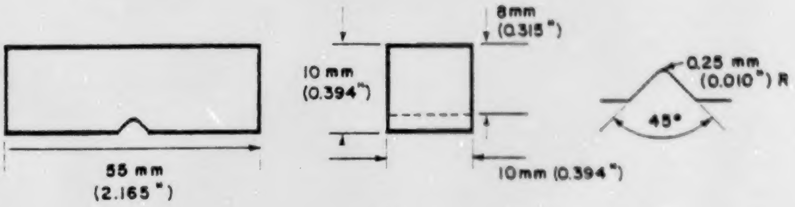
Figure 15-7-2. Charpy simple-beam impact test (top view).

is broken by a single blow of the pendulum, applied at the middle of the span. As a rule, the specimen breaks at the notch, the two halves fly away and the pendulum passes in between the two parts of the anvil. Fall distance (of the pendulum), less the height of its rise, gives the amount of energy absorption by specimen (plus friction losses and energy of flying pieces, normally considered to be from 1 to 2 foot-pounds).

The instrument has a scale and moving pointer (calibrated in terms of energy) to give "impact value" of test specimen. Because several variables usually are present in a specimen (quality of machining, location and extent of nonmetallic inclusions), it is best to test at least three specimens to arrive at a significant value. In the Charpy impact test, either a V notch or a key-hole notch (Figure 15-7-3) may be used in the specimen. Typically the v-notch specimens have been widely used in nuclear technology due to the large amount of test data using this type of test specimen.


5 mm
(0.197")
2 mm
(0.079")
10 mm
(0.394")
55 mm
(2.165")
10mm (0.394)
SAW CUT
1.6 mm ($\frac{1}{16}$")
OR LESS

KEY-HOLE NOTCH


8mm
(0.315")
10 mm
(0.394")
0.25 mm
(0.010") R
45°
55 mm
(2.165")
10mm (0.394")

V NOTCH

Figure 15-7-3. Charpy impact test specimens.

Additional details about the applications of the Charpy V-Notch Test will be discussed in 30-7 which considers Reactor Pressure Vessel Inspection.

IZOD TEST

In an Izod test, the specimen is held rigidly in the vise of the impact-testing machine (Figure 15-7-4), as a cantilever beam, with the center of the notch coincident with the upper face of the jaws. With this method, one half of the test specimen is broken off, and the impact value is calculated as for the Charpy impact test.

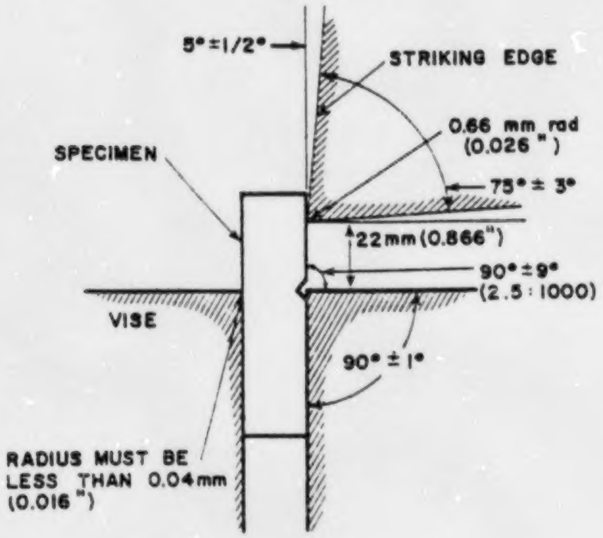

5° ±1/2°
STRIKING EDGE
0.66 mm rad
(0.026")
SPECIMEN
75° ± 3°
22mm (0.866")
90° ±9°
(2.5 : 1000)
VISE
90° ± 1°
RADIUS MUST BE
LESS THAN 0.04mm
(0.016")

Figure 15-7-4.
Izod (cantilever-beam)
impact test setup.

A test specimen for the Izod test (Figure 15-7-5) has the notch located near one end of the bar. The notch itself is the same as the V notch used in the Charpy test (45° angle).

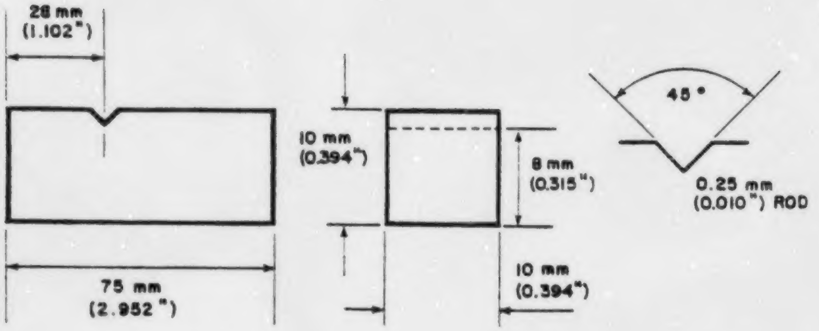


Figure 15-7-5. Izod (cantilever-beam) impact test specimen.

DROP-WEIGHT TEST

The drop-weight test is used for establishing a value for a temperature where brittle fracture becomes highly probable. Brittle fracture may start at nominal levels of stress provided certain other conditions are satisfied. These conditions are:

1. A flaw such as a crack is present.
2. A stress of sufficient intensity to develop a small deformation at the crack tip is applied.
3. A temperature low enough to promote cleavage fracture of the deformed metal crystals.

The dropweight test utilizes specimen samples that are 5 in. x 2 in. x 5/8 in. to determine this "brittle fracture temperature" or "nil-ductility temperature," T_{NDT}. A typical impact energy for breaking this dropweight sample is about 250 ft. lbs.

The dropweight test is performed as shown in Figure 15-7-6.

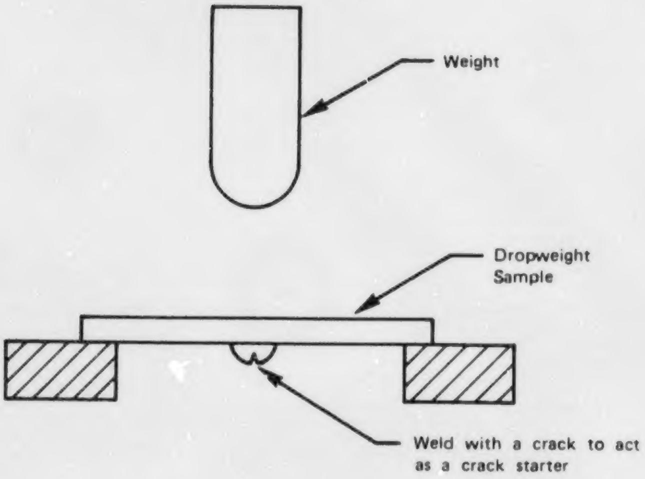


Figure 15-7-6 The Dropweight Test

The "drop-weight nil-ductility temperature," T_{NDT}, is the temperature below which steel, in the presence of a cleavage crack (usually a weld deposited on one side of the test piece with a crack in it), will not deform plastically before fracturing, but will fracture at the moment it begins to yield.

This test is basically a "go, no-go" test in that the specimen will either break or fail to break. The drop-weight test is surprisingly reproducible as cited in the Metals Handbook 8th Edition, Volume 10, page 38:

> "For example Pellini made 82 tests of specimens from one plate of low carbon steel. At 30°F and 40°F, all specimens remained unbroken. At 20°F, only one of 14 specimens broke; however, at 10°F, 13 of 14 specimens broke. At temperature below 10°F, all specimens broke."

As a result, the drop-weight test plays an important role in the determination of the temperature in which brittle fracture can occur in steel. This is particularly important when reactor pressure vessel safety and integrity are concerned as is discussed in Module 30-7 which considers Reactor Pressure Vessel Inspection and explains how the drop-weight T_{NDT} is measured, for the reactor vessel material and then the Charpy V-Notch Test is performed on the same material to verify this temperature.

FATIGUE

Fatigue is the progressive localized permanent structure change that occurs in a material subjected to repeated or fluctuating strains at stresses having a maximum value less than the tensile strength of the material. Fatigue may culminate in cracks or fracture after a sufficient number of fluctuations.

Fatigue fractures are caused by the simultaneous action of cyclic stress, tensile stress and plastic strain. If any one of these three is not present, fatigue cracking will not initiate and propagate. The cyclic stress starts the crack; the tensile stress produces crack growth (propagation). Although compressive stress will not cause fatigue, compression loads may do so. There isn't a single value of stress which will cause fatigue to occur, instead there is a range of stress in which it can be produced.

In early literature, fatigue fractures were attributed to "crystallization", because of their crystalline fracture appearance. But metals are crystalline solids, and therefore the use of the term crystallization in connection with fatigue is confusing and should be avoided.

The process of fatigue may be considered as consisting of three stages:

1. Initial fatigue damage leading to crack initiation.
2. Crack propagation until the remaining uncracked cross section of a part becomes too weak to carry the loads imposed.
3. Final, sudden fracture of the remaining cross section.

PREDICTION OF FATIGUE LIFE

In practice, prediction of the fatigue life of a material is complicated because, except for a few relatively brittle materials, the fatigue life of a material is very sensitive to small changes in loading conditions, local stresses and local characteristics of the material. Because it is difficult to account for these minor changes in either the dynamic stress-prediction techniques or in fatigue-failure criteria, there is a large uncertainty inherent in analytical predictions of fatigue life. Thus, the designer also is required to rely on experience with similar parts and eventually on qualification testing of prototypes or production parts. Although laboratory fatigue tests performed on small specimens are not sufficient for precisely establishing the fatigue life of a part, it is useful to examine these data because laboratory tests (a) are the major source of fatigue-failure criteria, (b) isolate the loading variables involved in fatigue, (c) are useful in rating materials in terms of their relative resistance to fatigue, and (d) can be used to establish the relative importance of such items as fabrication method, surface finish, heat treatment, assembly technique and environment on the fatigue life.

In general, fatigue life can be expected to depend on the following:

1. Type of loading (uniaxial, bending, torsional)
2. Shape of loading curve.
3. Frequency of loading cycling.
4. Loading pattern (periodic loading at constant or variable amplitude, programmed loading or random loading).
5. Magnitude of stresses.
6. Part size.
7. Fabrication method and surface roughness.
8. Operating temperature.
9. Operating atmosphere.

Traditionally, fatigue life has been expressed as the total number of stress cycles required for a fatigue crack to be initiated and then to grow large enough to produce catastrophic failure (separation of the specimen into two pieces). In this article, fatigue data are expressed in terms of total life.

FATIGUE TESTS

The fatigue strength of a material is indicated by the maximum stress it can sustain (for a specified number of stress cycles) without failure. (The stress is completely reversed within each cycle unless otherwise stated.) Fatigue resistance of a material, then, is its favorable reaction to loads applied more than once. Fatigue strength, though usually proportional to tensile strength, does not correlate over wide ranges of tensile strengths.

Metals are not perfectly homogeneous but consist of crystals within planes of cleavage, or are "slip" oriented in many directions. When enough stress is applied, slipping takes place on planes within the individual crystalline grains. The slipping may not be sufficient, at first, to cause trouble. But continued or repeated slipping, of sufficient magnitude, ultimately causes minute cracks to form and propagate. Gradually the area of sound metal remaining in any cross section is reduced. One of the unsolved problems of metal fatigue is exact determination of when and how, under repeated stress, harmless slip changes to harmful slip.

ROTATING-BEAM FATIGUE TEST

The most commonly used method of fatigue testing consists of submitting specimens (or an entire structural or machined part) to cycles of known loads. The number of cycles required for fracture (or for arriving at a given specified "life" prior to fracture) are noted. The results of the test are plotted on an S-N diagram (Figure 15-7-7), in which the maximum load or stress is plotted as an ordinate, and the number of cycles for fracture as an abscissa.

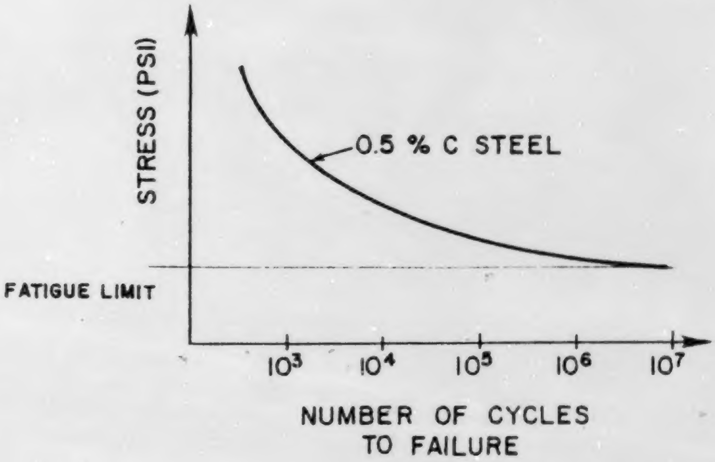


Figure 15-7-7.
S-N curve.

If the S-N curve becomes horizontal, the level of alternating stresses that can be sustained indefinitely by a material has been reached; this stress is called the "fatigue limit." For carbon steels, this limit is generally taken after 10 million (10^7) reversals.

Essential parts of a fatigue-testing machine (Figure 15-7-8) include:

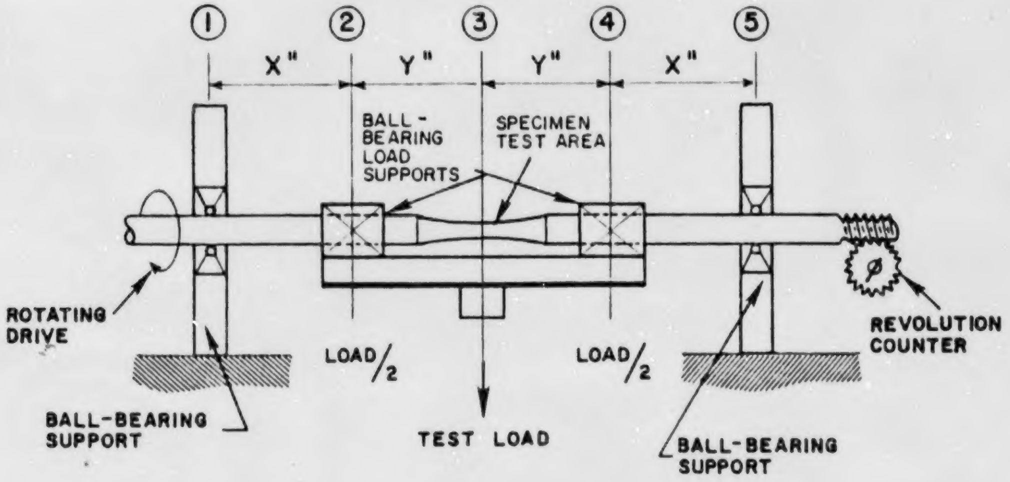

①
②
③
④
⑤
X"
Y"
Y"
X"
BALL-BEARING LOAD SUPPORTS
SPECIMEN TEST AREA
ROTATING DRIVE
BALL-BEARING SUPPORT
LOAD/2
LOAD/2
TEST LOAD
BALL-BEARING SUPPORT
REVOLUTION COUNTER

Figure 15-7-8. Rotating-beam fatigue-testing machine.

Rotating drive (for applying repeated cycles of stress to specimen).

Measuring device (for determining maximum and minimum stresses applied during cycle).

Counter (for indicating cycles of stress applied to specimen).

Breaking device (for stopping test machine automatically when specimen breaks).

REPEATED BENDING (DIRECT-FLEXURE) TEST

Repeated bending, or direct flexure, provides another important fatigue test in which a specimen is bent back and forth (but not rotated). This procedure is especially useful in testing flat-rolled products. Surface preparation of the specimen is not necessary, thus the test can be made on specimens that have a surface exposed while in service.

RESONANT-FREQUENCY (DIRECT-FLEXURE) TEST

The resonant-frequency test consists of vibrating a specimen (at its fundamental frequency) with an oscillating, applied force. Because of the characteristics of resonant vibrations, very small forces applied at the resonant frequency of a specimen are capable of producing large amplitudes of vibration and correspondingly high stresses. Specimens with relatively large cross sections can be tested in this manner: very large test machines would be required if mechanical loading were used.

TORSION TESTING

Torsion is the term used to indicate a condition in which a body undergoes twisting (Figure 15-7-9). In a torsion test,

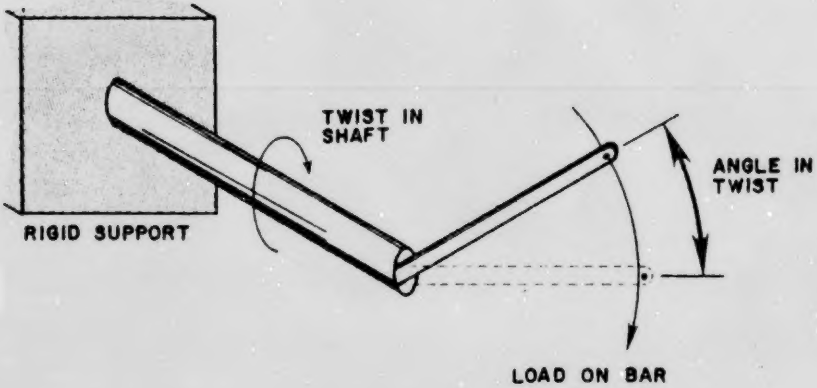


Figure 15-7-9. Twist occurs when torsion load is applied.

the specimen is subjected to twisting (torsional loading) similar to that encountered by drive shafts or crank shafts. Data obtained on torsional strength, particularly yield points (yield strengths) are highly important to designer of such structures.

Data for torsion tests are usually obtained in the form of a torque-twist curve, in which applied torque is plotted against angle of twist. Torsion produces a state of stress known as "pure shear," and shear stress at yielding can be calculated from 1) measured torque at yielding and 2) dimensions of specimen being tested.

EXERCISES

None.

MATERIALS

Milling machine.
Charpy V-notch bar, machined from SA-36 or SA-516.
Impact-test machine, similar to one described in this module.
Bar of steel (1/2" diameter, 6 to 8" long).
Vise.

PROCEDURES

OPERATING PROCEDURE FOR IMPACT TEST

1. Use three v-notch Charpy impact-test specimens made of SA-36 or SA-516 steel.
2. Inspect test specimens; be sure they match dimensions given in this module and that notches are smooth; specimen temperatures should be between 21°C and 32°C (70°F and 90°F).
3. Before a specimen is placed in position to be tested, check machine (make a free swing of the pendulum). With indicator at the initial position, the free swing should indicate "zero energy."
4. Place a test specimen in machine; test specimen should be centered so that head strikes directly in center of notch. If an end-centering device is used, caution must

be taken to ensure that low-energy, high-strength specimens do not rebound into pendulum and cause erroneously high recorded values.

5. Let pendulum strike specimen with an energy of from 220 to 265 ft lb and a linear velocity (at point of impact) of 16 to 19 ft per sec.
6. Set energy indicator at its initial position; place test specimen in proper position on specimen rest; release pendulum smoothly. (This entire sequence should take less than 5 seconds.) If specimen fails to break, do not repeat blow; check to see if failure to break resulted from extreme ductility of specimen or lack of sufficient energy in blow. If a specimen jams in machine, disregard results and check machine thoroughly for damage or maladjustment.

   To avoid recording an erroneous value (caused by jarring indicator when locking pendulum in upright position), read indicated value from indicator prior to locking pendulum for next test.
7. Record values from all tests on Data Table 15-7-1; calculate average value.

OPERATING PROCEDURE FOR TORSION TEST

1. Use steel bar (1/2" dia., 6-8" length); clamp bar horizontally into a vise; clamp 24" lever arm to end of bar (Figure 15-7-10); situate lever arm vertically; hang bucket from end.

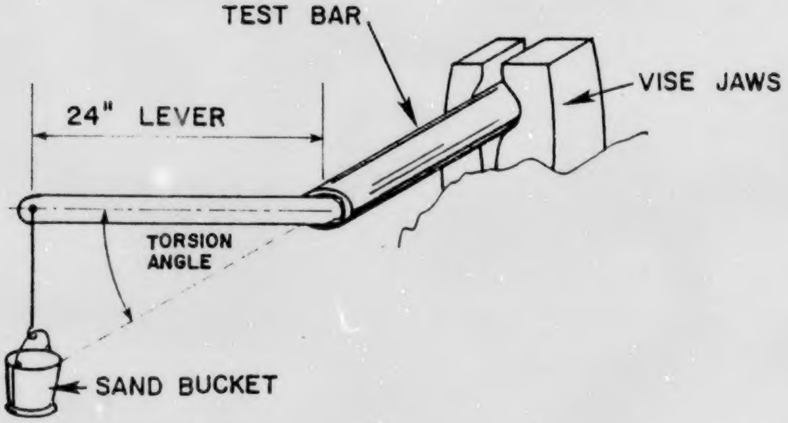

TEST BAR
VISE JAWS
24" LEVER
TORSION ANGLE
SAND BUCKET

Figure 15-7-10. Torsion test setup.

2. Fill bucket with sand; measure angular deflection of lever arm at increments of 5 pounds; add weight up to 100 lbs, or to breaking point of rod; record deflections on Data Table 15-7-2.
3. From instructor, obtain calculated shear stress limits. Is there a difference between calculated and measured limit? Why?

DATA TABLE 15-7-1

Specimen No.	SA 36 (Ft Lbs)	SA 516 (Ft Lbs)
1		
2		
3		

DATA TABLE 15-7-2

Bucket Load (Lbs)	Angle of Twist (°)	Shear Stress (Act)	Shear Stress Calculated (by Instructor)

REFERENCE MATERIALS

American Society for Testing Materials (ASTM). 1976 Book of ASTM Standards, Parts 3 and 10. Philadelphia, PA: ASTM, 1976.

Dieter, G.E. Mechanical Metallurgy. New York: McGraw-Hill, 1961.

Metals Handbook, Volume 10, 8th Edition, Failure Analysis and Prevention, 1975.

TEST

Read each question carefully. Be sure your responses provide the specific information each question requires. Be brief.

1. What is "toughness" of a metal?

2. How would toughness affect a metal's elastic limit and its ductility?

3. In general, what is the cause of fatigue failure? Where is fatigue failure thought to originate?

4. In fatigue failure, if the load at a region of high stress concentration remains constant, the stress increases as the crack become larger. Why does this happen?

5. What is slip? What causes slip?

6. How does the size of a part affect its fatigue strength?

7. What is the purpose of the Charpy test?

8. Write "yes" in front of all correct statements about the Charpy test. Write "no" in front of all incorrect statements.

_____ a. The Charpy test evaluates the transition from brittle to ductile fractures in steel.

_____ b. The Charpy test tests the impact behavior of the specimen.

_____ c. The Charpy test reproduces the ductile-brittle transformation of steel in about the same temperature range actually observed in engineering structures.

_____ d. The Charpy test demonstrates that there is usually a single temperature at which the average ferrous metal usually becomes brittle.

_____ e. The energy expended in fracturing the impact specimen is the quantity measured by the Charpy test.

_____ f. The results of the Charpy test are the same, regardless of the type of notch used.

_____ g. In the Charpy test, only one specimen of a given metal needs to be tested to arrive at a significant valve.

_____ h. The energy absorption of the Charpy specimen is given by the fall distance of the pendulum, less the height of its rise.

9. Briefly describe how the rotation-beam fatigue test is done.

____

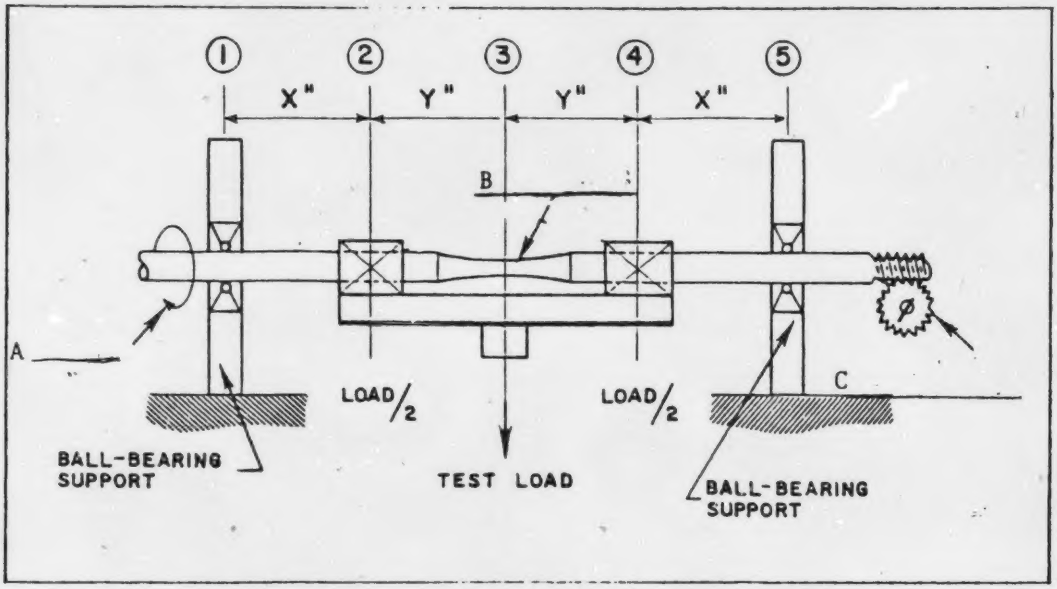
____

____

____

____

10. Label the parts (areas) of the rotating-beam fatigue testing machine to which the arrows point.



①
②
③
④
⑤
X"
Y"
Y"
X"
B
A
C
LOAD/2
LOAD/2
BALL-BEARING SUPPORT
TEST LOAD
BALL-BEARING SUPPORT

11. Name and very briefly describe one type of fatigue testing, besides the rotating-beam test.

____

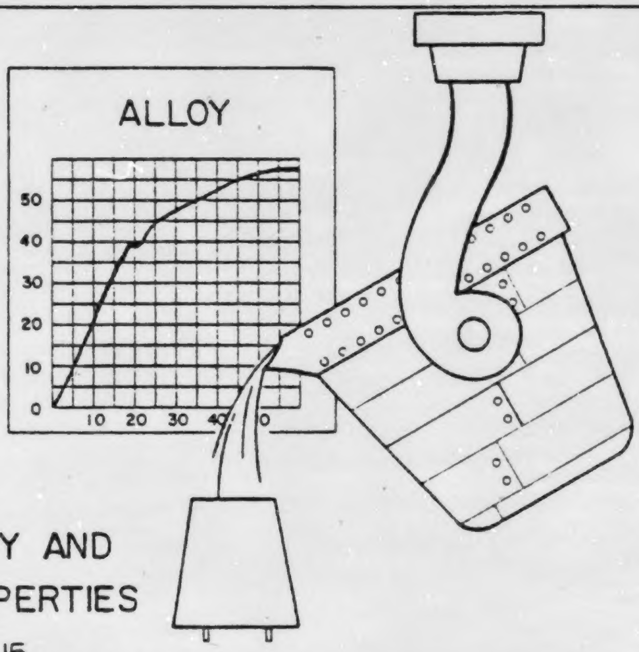
____

____

____

NUCLEAR TECHNOLOGY

MODULE 15-8 FAILURE MECHANISMS IN METALS


ALLOY
50
40
30
20
10
0
10
20
30
40
50

METALLURGY AND
METALS PROPERTIES
COURSE 15

COURSE MODULES

COURSE 15 METALLURGY AND METALS PROPERTIES

	MODULE 15-1	Fabrication Processes for Metals
	MODULE 15-2	Chemical Analysis of Metals
	MODULE 15-3	Basic Metallurgical Concepts
	MODULE 15-4	Properties of Steel
	MODULE 15-5	Metallographic Examination
	MODULE 15-6	Mechanical Testing - Tensile, Bend, Hardness
	MODULE 15-7	Mechanical Testing - Impact, Nick Break, Fatigue
⇨	MODULE 15-8	Failure Mechanisms in Metals

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INTRODUCTION

Probably no aspect of the mechanical properties of materials commands more widespread interest than the one termed "failure." Although striking differences in the resistances of various materials to cracking have long been recognized, the reasons for these differences remain only partly understood. Present theoretical models of fracture explain relative brittleness of glass compared with steel or the brittleness of zinc compared with copper, but not the brittleness itself.

This module explores the general subject of failure mechanisms in metals. Also, it covers effects of radiation on material properties, a complex phenomenon. Each type of radiation has its own particular characteristics, and each class of materials responds to each type of radiation in its own particular fashion.

MODULE PREREQUISITES

The student should have completed courses in physics and chemistry, and all prior modules in this Course.

OBJECTIVES

Upon completion of this module, the student should be able to:

1. Describe the Griffith theory and the high-temperature crack nucleation theory.
2. List and explain the effects of nuclear radiation on structural metals.
3. Describe the annealing of damage induced by radiation.
4. Test the effects of irradiation and temperature on metal properties.

MECHANISMS OF FAILURE

Each advance in understanding of the relationships between structure and crack propagation brings with it a possibility of developing new useful materials or of improving the properties of those in current use.

GRIFFITH THEORY

Griffith explained the weakness of glass by proposing that microcracks are always present. His theory showed that when applied stress was below a critical level, it was impossible for a microcrack of a given size to grow, but above this level it could grow. Thus, "critical stress for growth" was likely to be catastrophic as soon as a critical stress corresponding to initial crack size was reached.

If a plate of unit thickness (Figure 15-8-1) has a

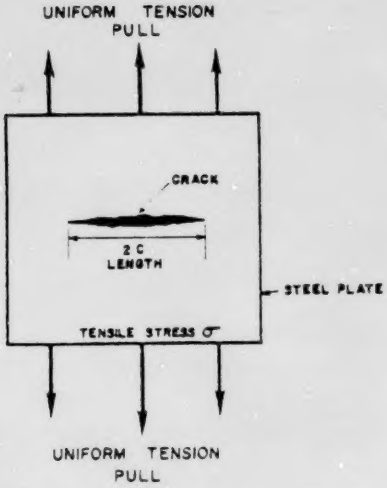

UNIFORM TENSION PULL
CRACK
2 C LENGTH
STEEL PLATE
TENSILE STRESS σ
UNIFORM TENSION PULL

Figure 15-8-1. Griffith crack.

crack of length 2C, which extends entirely through it, and the plate is subjected to a uniform tensile stress acting at right angles to the plane of the crack, the local stress just above and below the crack will be less than σ, and local stress at the two ends of the crack will be greater than σ.

The procedure for calculating critical average stress (necessary to allow the crack to grow) used by Griffith, expressed strain energy of the system as a function of crack dimensions and applied stress:

$$\sigma_{crit} = 2\left[\frac{\gamma E}{\pi C}\right]^{\frac{1}{2}}$$

Equation 15-8-1
(Equation = Eq.)

Where:

γ = is Poisson's Ratio. This is the absolute value of the ratio of transverse strain to the corresponding axial strain, in a body subjected to stress along its axis. Poisson's Ratio is about 0.3 for most metals.

C = half of crack length.

E = Young's modulus for material. This is a measure of the rigidity of the metal. It is a ratio of the applied stress to the resultant strain within the range where the material returns to its original size when the stress is removed.

HIGH-TEMPERATURE CRACK NUCLEATION

At high temperature, metals creep and finally fracture at stresses much below the low-temperature tensile strengths. The motion of dislocations due to applied stress results in average concentrations of vacant lattice greater than the equilibrium values. Vacancies can be formed by several processes. The growth of cracks is termed nucleation. A nucleation site is where the crack starts and begins to propagate. Nucleation of carcks (large enough to grow catastrophically at the low stress levels involved in creep) almost certainly takes place by collections (voids) of these excess vacant lattice sites. The process termed as creep is a time-dependent strain occurring under stress.

Crack Propagation

The Griffith criterion must certainly be met before the growth of a crack can occur; however, there are other conditions to be met. Stress concentration in the material near the tip of a sharp crack can be relieved, either by motion of the crack-front to a new location, or by plastic deformation resulting in blunting of the crack tip. The choice between brittle and ductile behavior probably depends on which takes place first and can be affected by many factors, such as speed of crack-front, relative magnitude of shear and normal stresses, and minimum shear stress required to move dislocations in material.

If local plastic deformation prevents a crack from propagating in a brittle manner, it may be able to grow slowly by multiple nucleation and joining of new cracks just ahead of the main crack-front - probably the mechanism of shear fracture.

Crack nucleation, by any of the dislocation mechanisms, depends only on shear stress. If nucleation was the critical event, then the hydrostatic component of stress should have no effect on fracture strength; however, experiments clearly show that the presence of hydrostatic tension increases brittleness of a material. And, because thick sections and sharp notches promote brittleness, this presence suggests that nucleation is not the critical step.

Although many cracks may be nucleated by dislocation pile-ups, they may propagate to cause failures. In polycrystalline materials, cracks are often observed that have grown only across one grain. Before final parting of the specimen, many grains may contain cracks.

According to the Griffith criterion, a crack can continue to grow only as long as the stress in the vicinity remains larger than σ_{crit} or until a sudden decrease in applied stress occurs.

LOW TEMPERATURE BRITTLE FRACTURE

The propagation of cracks at high temperature has been studied extensively as described in the foregoing section. However, fractures of a catastrophic nature can also occur at low temperatures (at or below room temperatures). Generally, when metals fail at low temperatures, they tend to do so in a brittle manner. Although the exact mechanism of brittle fracture isn't thoroughly understood some brief history of its study and basic facts regarding the phenomena will now be considered.

In Boston, Massachusetts in 1919, a 2,300,000 gallon molasses tank fractured on a cold day and twelve men and four horses lost their lives in the disaster. This incident was isolated and it wasn't until World War II when interest in brittle fracture was greatly stimulated by the U.S. Naval Research Laboratory. The reason being that 250 U.S. ships experienced brittle fracture in various degress of severity. Ninteen of these ships broke in half. In each incident the temperature was about 40°F. The results of the Naval Research Laboratory study is outlined in the following paragraphs.

When tensile specimens are tested at lower and lower temperatures, there exists a temperature at which the yield strength equals the ultimate strength. This is shown as NDT in Figure 15-8-2. At temperature, NDT, there is no measureable ductility.

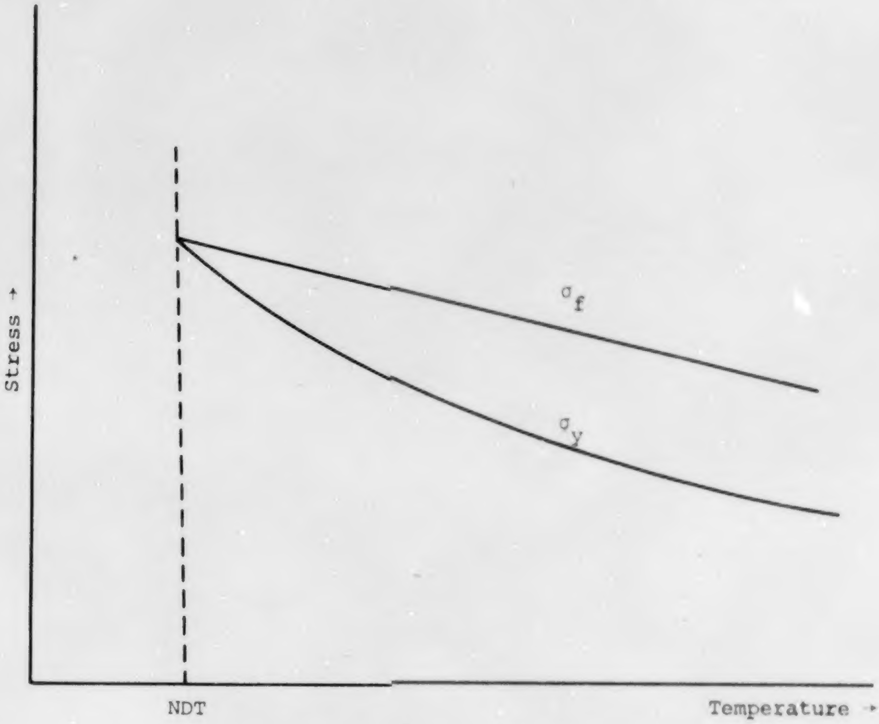


Figure 15-8-2 Stress vs. Temperature Curve Showing Plot of Failure Stress (σf) and Yield Stress (σy).

The point on Figure 15-8-2 labeled as NDT is called the nil-ductility temperature and is affected by several metallurgical variables. It is therefore, not a material's constant and cannot defined exactly, but can be defined under a given set of conditions including grain size, etc.

Module 15-6 examined the typical stress-strain curves where it was shown that the yield point (or yield stress) is typically much lower than the rupture stress (or failure stress). However, here in Figure 15-8-2, it is shown that at a sufficiently low temperature (called the nil-ductility temperature) the yield stress and failure stress are one and the same. That is to say, when brittle fracture occurs the specimen fails at the instant it begins to yield.

This is of particular concern in a nuclear power station because if the reactor pressure vessel were to fail in a brittle manner, the results could be catastrophic. Module 15-7 introduced the concept of the brittle fracture. In this module it was mentioncd that brittle fracture was characterized by:

- a flaw, such as a crack, is present.
- a local stress of sufficient intensity to develop a small deformation at the crack tip is applied.
- a temperature exists which is low enough to promote cleavage fracture of the deformed metal crystals.

Let us now examine how the temperature for nil-ductility or brittle fracture is measured.

DETERMINATION OF THE REFERENCE TEMPERATURE FOR NIL-DUCTILITY (RT_{NDT})

An accurate determination of the nil-ductility temperature for a reactor pressure vessel is, therefore, very important. Title 10, Part 50 (10-CFR-50), Appendix G specifies that the ASME Code must be followed in order to precisely determine this nil-ductility temperature. 10-CFR-50, Appendix G specifies that this nil-ductility temperature must be determined by two impact tests, the Drop-weight Test and the Charpy V-Notch Test. Both of these tests were described in some detail in Module 15-7. 10-CFR-50 and the ASME Code stipulate that the nil-ductility temperature must be measured in the following manner and must be specified as the Reference Temperature for Nil-Ductility, RT_{NDT}. This is so as not to confuse this temperature for nil-ductility with similar temperature measurements using other techniques. Within the past 35 years various techniques have been employed to measure this nil-ductility temperature and a number of different designations for this temperature may be found in the literature on brittle fractures. These include:

- NDT (Nil-Ductility Temperature)
- NDTT (Nil-Ductility Transition Temperature)
- DTT (Design Transition Temperature)
- RTT (Reference Transition Temperature)

However, today the Reference Temperature for Nil-Ductility, RT_{NDT}, is used for identifying this nil-ductility condition. The Reference Temperature for Nil-Ductility, RT_{NDT}, is determined by correlating the results of two tests.

1. The Drop-Weight Test (discussed in Module 15-7)
2. The Charpy V-Notch Test (discussed in Module 15-7)

1. The Drop-Weight Test

This test establishes a value for a temperature where brittle fracture becomes highly probable. The drop-weight test utilizes specimen samples that are 5 in. x 2 in. x 5/8 in. and 6 to 8 samples are typically used to establish a drop-weight nil-ductility temperature, T_{NDT}. A typical impact energy for breaking this drop-weight sample is about 250 ft. lbs.

The drop-weight test is performed as was shown in Figure 15-7-6. The weight is dropped from various heights so as to obtain different values of impact energy. T_{NDT} is then determined by:

a. Determining the temperature at which 2 samples didn't break. (This will typically be about $0^{\circ}F$.)

b. Then lower the specimen temperature by $10^{\circ}F$ and perform the drop-weight test again. If the samples break at this temperature, then this temperature is the Drop-weight Nil-Ductility Temperature, T_{NDT}.

2. Charpy V-Notch Test

Now, at a temperature no greater than ($T_{NDT} + 60^{\circ}F$), test three Charpy V-Notch specimens (C_V) as shown in Figure 15-7-3.

a. Each of these specimens is now cracked using the Charpy V-Notch Test as shown in Figure 15-7-2. Typically, two types of swinging pendulums are used in the Charpy V-Notch test. These are of 120 ft. lbs., and 200 ft. lbs. of impact energy, respectively. The energy lost in breaking the specimen can be determined by measuring the resultant energy of the pendulum.

   In this way, the sample is always broken on the first impact and there is no case of more than one impact necessary.

b. The ASME Code specifies that each of these Charpy specimens (C_V) shall exhibit at least 35 mils (0.035 in) of lateral expansion and require 50 ft-lbs., of impact energy to crack the sample in order to identify that there was some plastic deformation of the sample prior to it fracturing.

c. The 35 mils of lateral expansion is on the impact side of the Charpy specimen and indicates that the specimen fracture is particially ductile. A sketch of the 35 mils expansion is shown in Figure 15-8-3.

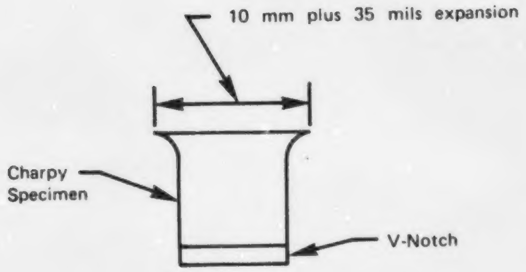


Figure 15-8-3 Cross-Sectional View of the Cracked Charpy V-Notch Specimen Showing 35 mils of Lateral Expansion

d. In the event that any specimen in step 2 does not meet these specified conditions, conduct additional C_V tests (in groups of 3 C_V specimens) to determine the temperature T_{CV} at which 50 ft. lbs., and a minimum of 35 mils lateral expansion are met. From this value of T_{CV}, then RT_{NDT} can be determined as follows:

$$RT_{NDT} = T_{CV} - 60^{\circ}F$$

so long as RT_{NDT} is greater than T_{NDT}. These procedures apply to Charpy samples from:

- The base material
- The heat affected zone (HAZ) in the weld region
- The weld material itself

Therefore it is important that the RT_{NDT} for the reactor vessel be precisely measured. However, experimental evidence also discloses that fast neutron irradiation will cause RT_{NDT} to increase. At this time, let us now examine these radiation effects.

NUCLEAR RADIATION EFFECTS IN STRUCTURAL METALS

Radiation effects in metals are produced primarily by fast neutron bombardment of the crystalline lattice structure of the metal. This is of the particular importance in reactor pressure vessels because the fast neutron irradiation damage can cause the reactor vessel to possess a higher probability for brittle fracture at ambient (room temperature) conditions. To examine this phenomenon more closely, let us consider what occurs when fast neutrons strike the reactor vessel wall.

Experimental evidence discloses that neutrons whose energy is in excess of 1 MeV cause damage to reactor vessel and structural materials by means of a direct collision with the atoms of that material. The atoms are knocked out of their lattice positions and are termed "knocked on" atoms. This results in vacancies in the crystalline material of the vessel. The "knocked on" atoms must be accomodated elsewhere. It must "squeeze in" between other atoms as shown in Figure 15-8-4. It is now termed as an "interstitial atom." This produces an effect on the metal which is similar to what is termed "work hardening." The hardness and tensile strength of the metal will increase, but the metal tends to become more brittle.

The elevated temperature of the reactor vessel during full power operation (about 580°F) will allow some movement of these interstitial atoms due to the increased crystalline lattice vibration at these elevated temperatures. This will result in some of the vacancies to be refilled by the movement of interstitial atoms thus causing a small annealling effect. However, it requires temperatures of greater than 1000°F to produce significant annealling effects.

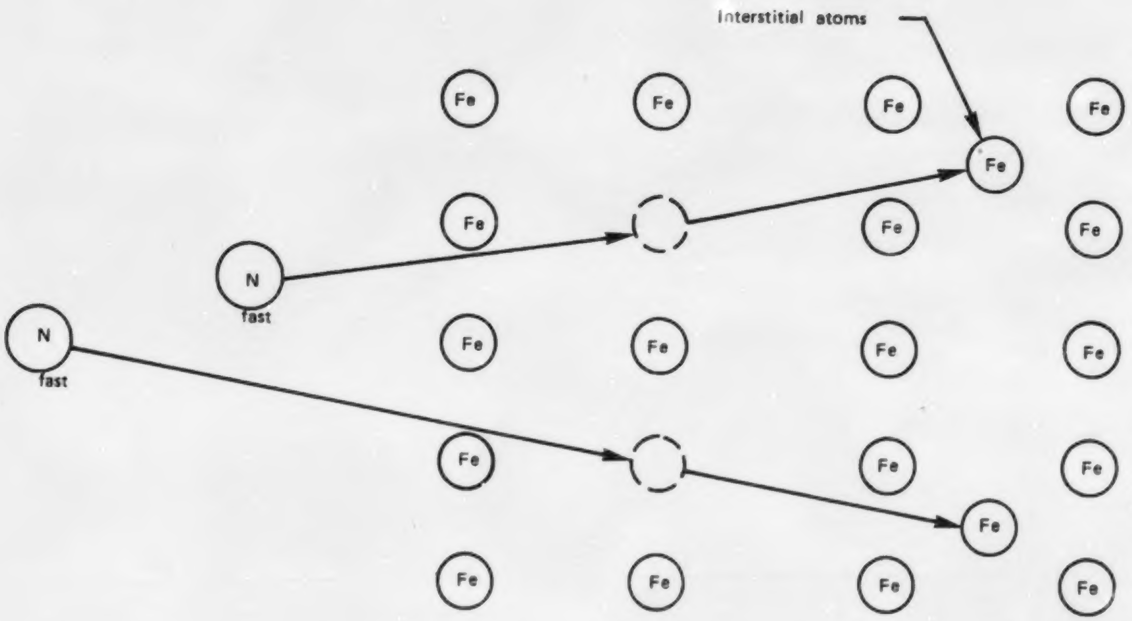


Figure 15-8-4 Fast Neutrons (>1 MeV) producing Interstitial Atoms Within the Crystalline Lattice Structure.

Because the fast neutrons cause the presence interstitial atoms within the crystalline lattice structure, this results in the reactor pressure vessel to become more subject to brittle fracture as a function of irradiation time. The section which follows examines this particular characteristic.

SHIFT IN RT_{NDT} OVER REACTOR VESSEL LIFETIME

Neutron irradiation of the reactor vessel produces damage to the metal's crystalline lattice structure, which increases the yield strength of the material, but it also increases the temperature at which brittle failure will occur. Because of this, the RT_{NDT} of the reactor vessel will increase over core life. An increase of 250°F is not uncommon. Figure 15-8-5 shows this variation and shows that it is also a function of the copper content of the carbon steel reactor vessel.

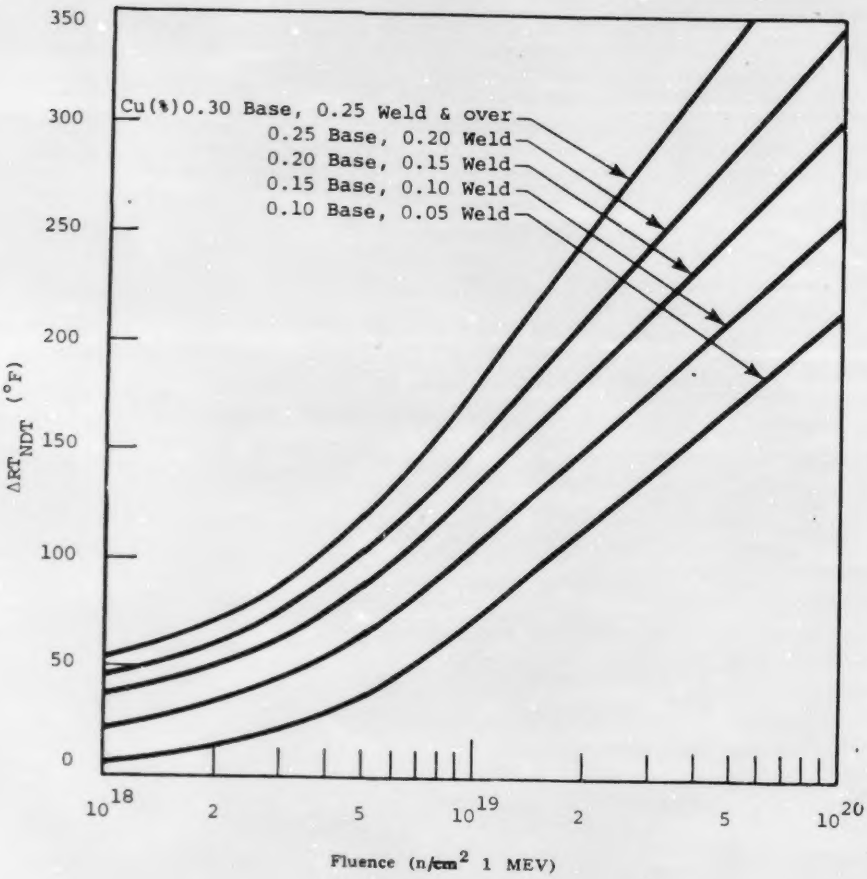


Figure 15-8-5 Effect of Fluence and Copper Content on Shift of RT_{NDT} for Reactor Vessel Steels Exposed to 550°F Temperature.

Since brittle failure must be avoided at all cost, the stresses imposed on the vessel from pressure and temperature gradients must be limited to a safe value. These considerations are used to establish temperatures above which the system may be pressurized and to establish heatup and cooldown limitation curves for the reactor coolant system.

As shown in Figure 15-8-5, the shift in RT_{NDT} (or ΔRT_{NDT}) depends upon the time integrated fast neutron flux, or fluence. The fluence is readily a product of the neutron flux, ϕ, times the time, t.

$$\text{Fluence} = \phi\left(\frac{\text{neutrons}}{\text{cm}^2\ \text{second}}\right) \times t\ (\text{seconds}) \qquad \text{Equation 15-8-2}$$

$$\text{Fluence} = \phi \times t \ \left(\frac{\text{neutrons}}{\text{cm}^2}\right)$$

For a typical pressurized water reactor (PWR), for example, the average fast neutron flux in the core at full power is about 10^{14} neutrons/cm^2 sec. This results in about 5×10^{10} neutrons/cm^2 sec at the reactor vessel wall. Assuming an effective 32 full power year design lifetime (about 40 years of actual life) results in the following estimated time integrated flux or fluence. Using equation 15-8-2 one obtains the following fluence of 32 effective full power years of reactor core operation:

$$\phi \times t = 5 \times 10^{10}\ \frac{\text{neutrons}}{\text{cm}^2} \times 32 \times 3.158 \times 10^7$$

$$\phi \times t \approx 5 \times 10^{19}\ \text{neutrons/cm}^2$$

As can be seen from Figure 15-8-5, this would cause a shift in RT_{NDT} of no less than 200°F and possibly as much as about 350°F depending upon the copper content in the steel. Recall from Module 15-1, it was mentioned that there are trace amounts of copper in carbon-steel. The copper atoms are apparently more easily knocked out of their crystalline lattice locations by the faster neutrons than the iron atoms. Hence, ΔRT_{NDT} tends to be sensitive to the copper content as shown in Figure 15-8-5.

Additional discussion regarding the details of how the shift in RT_{NDT} will affect the heatup and cooldown limitations is covered in detail in Module 30-7 entitled Reactor Pressure Vessel Inspection.

Let us now consider some general fast neutron radiation effects on the mechanical properties of steel.

FAST NEUTRON IRRADIATION EFFECTS ON THE MECHANICAL PROPERTIES OF STEEL

Mechanical property changes induced by radiation can be sufficiently substantial to influence component design and materials selection.

Increased yield strength, tensile hardness and brittleness almost always result from neutron bombardment, provided the temperature is not high enough for annealing. (Partial annealing can occur well below the recrystallization temperature.) Radiation generally strengthens metals in almost any initial condition, but the effect is more pronounced with softer starting conditions. Radiation strengthening has about the same magnitude obtained by other means except when the potential increase in strength (by working) cannot be realized due to low ductility (Figure 15-8-6). Changes

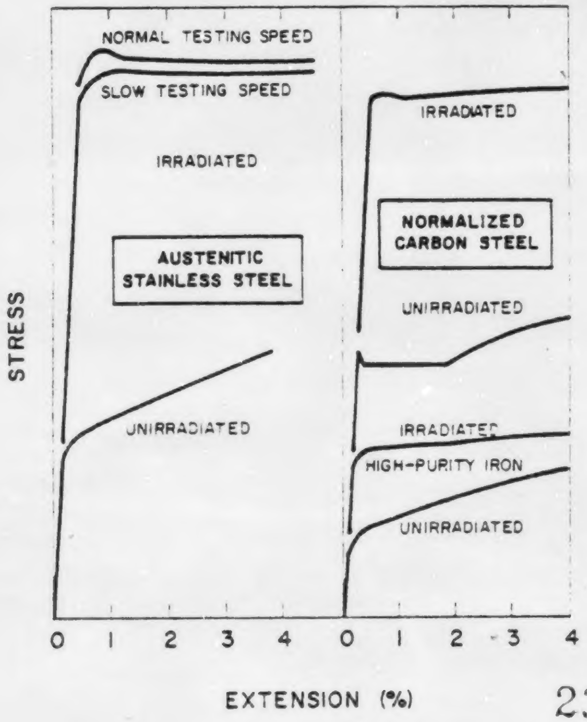


Figure 15-8-6. Effect of radiation on stress-strain characteristics of some iron-based alloys.

in strength and hardness for some common metals and alloys are indicated in Table 15-8-1.

TABLE 15-8-1

EFFECT OF RADIATION ON TENSILE PROPERTIES OF SELECTED ALLOYS

	Yield Strength, psi		Tensile Strength, psi		Ratio of Yield Strength to Tensile Strength	
	Pre	Post	Pre	Post	Pre	Post
1100-H14	18,000	23,000	20,000	27,000	0.9	0.85
1100-0	7,000	17,000	17,300	26,000	0.51	0.65
High-purity iron	18,000	31,000	36,000	37,000	0.5	0.84
Normalized carbon steel	50,000	93,000	75,000	97,000	0.67	0.96
Hardened and tempered alloy steel	153,000	196,000	164,000	198,000	0.93	0.99
Austenitic stainless steel	37,000	97,000	98,000	115,000	0.38	0.84

Yield strength generally increases more rapidly than tensile strength, which does not necessarily imply a decrease in plasticity prior to necking, although such a decrease is usually observed. The increase in strength may be regarded as beneficial provided there is no concurrent loss of ductility (where ductility is required).

Unusual effects in plastic deformation are found in many irradiated metals. The normal yield point in mild steels is altered under radiation to continuous yielding followed by a region of low work-hardening.

Ductility (measured by reduction of area and elongation) is generally reduced. Metals with low initial ductility appear to have relatively greater reductions in ductility from radiation than metals with high initial ductility. Some typical effects of radiation on ductility are given in Table 15-8-2.

TABLE 15-8-2
EFFECTS OF RADIATION ON DUCTILITY OF SELECTED ALLOYS

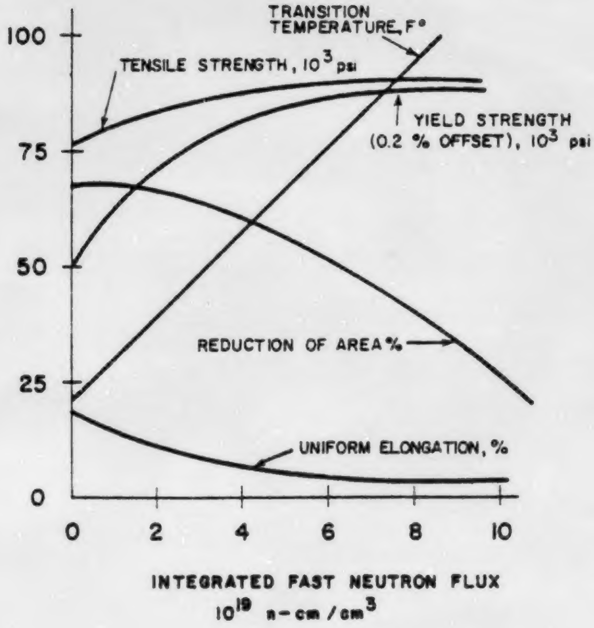
	Elongation Up to Maximum Load, %		Conventional Elongation, %		Reduction of Area, %	
	Pre	Post	Pre	Post	Pre	Post
1100-0 aluminum	--	--	38	21*	--	--
1100-H14 aluminum	--	--	22	20	81	75
Normalized carbon steel	22	5	--	--	65	26
Austenitic stainless steel	49	25	--	--	71	62
QMV beryllium	--	--	1.4	0.2	--	--
356 aluminum	--	--	2.7	0.6	--	--
Molybdenum	--	--	44	0	68	0

* Sheet specimens

In some materials (e.g., carbon steels) notch (impact) tests, rather than measurements of elongation or area reduction, are used to indicate a type of toughness. In carbon steels, radiation causes a loss of energy absorption in notch-impact tests and an increase in the temperature of transition between brittle and ductile behavior.

Structural metals are normally evaluated by their strength, ductility and resistance to impact. This evaluation may be difficult under radiation, since different properties do not have the same dependence on integrated neutron flux; for example, ASTM A-212-B carbon-silicon steel (Figure 15-8-7).

Figure 15-8-7.
Effect of radiation on properties of ASTM A-212-B carbon-silicon steel.



The effects of radiation on mechanical properties of this steel are presented in Table 15-8-3. Neutron dose also

TABLE 15-8-3

MECHANICAL PROPERTIES OF AN IRRADIATED ASTM A-212-B CARBON-SILICON STEEL

Integrated Neutron Flux	Strain Rate, in/in-min	Yield Stress, psi	Tensile Strength, psi	Reduction of area, %	Uniform Elongation, %
0	0.05	51,400	75,100	62	19
0	0.05	47,300	75,000	64	23
0	0.05	51,600	76,100	67	24
10^{19} nvt	0.05	65,400	80,800	68	18
10^{20} nvt	0.05	94,900	97,100	28	5.4
10^{20} nvt	0.05	92,600	97,000	24	4.6
0	0.5	50,700	76,700	64	23.2
0	0.5	52,600	78,800	58	20.2
10^{20} nvt	0.5	98,500	100,100	32	4.5
10^{20} nvt	0.5	94,500	97,800	35	12

affects stress-strain characteristics (Figure 15-8-8) and impact strength (Figure 15-8-9).

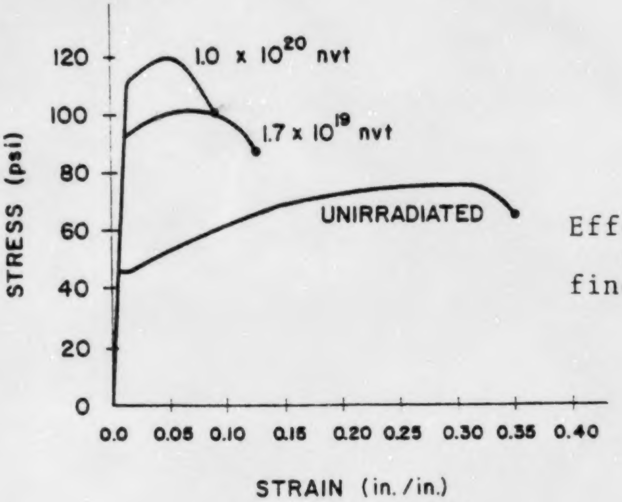


Figure 15-8-8.
Effect of radiation on stress-strain characteristics of fine-grain ASTM A-212-B carbon-silicon steel.

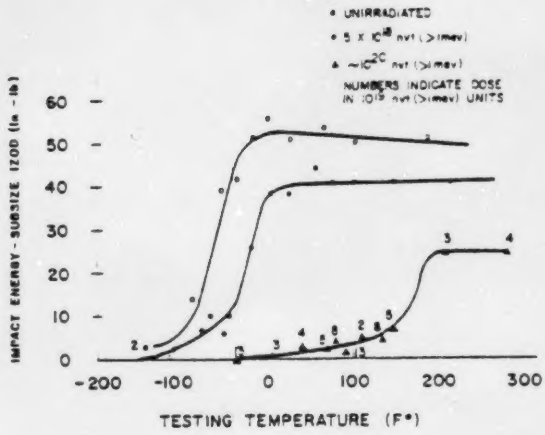


Figure 15-8-9.
Effect of radiation on impact strength of hot-rolled ASTM A-212-B carbon-silicon steel.

The ductile-brittle transition temperature, as determined by a notch (impact) test, is a semiquantitative measure of the minimum temperature at which stress may be applied in service without undue risk of brittle fracture. Radiation can raise this transition temperature of structural steels. For example, the effect of neutron dose on energy absorption (in impact) is a function of testing temperature (Figure 15-8-9). A large shift in transition temperature (arbitrarily defined as the 2 ft/lb energy absorption level) is obvious.

An approximate relationship between transition temperature and dose can be seen (Figure 15-8-10) for the different curves, each of which represents a different radiation temperature. Weld metal (B) apparently anneals more readily

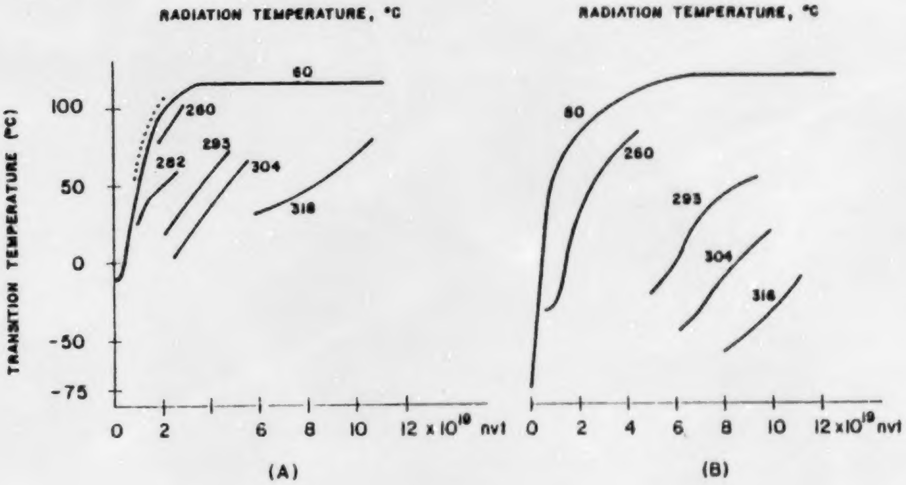


Figure 15-8-10. Effect of radiation dose and temperature on brittle-ductile transition temperature: (A) thick wrought plate; (B) weld metals.

than wrought plate (A).

ANNEALING OF DAMAGE

The defects discussed do not constitute a final state, since they have considerable mobility at all but very low temperatures, and can interact with each other and alter total damage. Irradiation must be performed at very low temperatures for all damage to be "frozen in" as it occurs. This process is complex, and it is not at all certain how it is accomplished. The annealing state of the radiation effects process is as important as the defect-causing state. Two types of annealing are considered:

Thermal.
Radiation.

If certain properties of a material are measured at room temperature, irradiated at a specified temperature and then remeasured, likely some change will be noted. If the material is then heated to a temperature somewhat higher than that of radiation and properties are again measured after cooling to room temperature, reversion toward preirradiation values occurs. This change is "thermal annealing."

If the cascade of point defects (electron displacement) is partially annealed by the associated brief temperature increase, this change is "radiation annealing."

EXERCISES

1. List several failure mechanisms in metals; describe how each metal failed and what could have been done to prevent failure.
2. Use a case history of some catastrophic metal failure (assigned by instructor); review case in detail; explain case to class. Include operating conditions (e.g., stresses, temperatures, vibration, irradiation) and what was done to prevent future failures. (Note: Cases may be taken from aircraft, pipeline, railroad, boiler, automotive or construction industries.)
3. Visit an independent metals testing laboratory and observe how failed metals are tested to determine the cause of failure; for each failed sample, find:

   Application of failed piece.
   Type of metal.
   Description of failed edges.
   Operating conditions.
   Cause of failure.

   Student should express an opinion as to how each particular application can be improved to prevent such failures. Use diagrams as required.
4. From ASME Boiler and Pressure Vessel Code, find requirements for taking tensile specimens of pressure vessel material over lifetime of vessel; answer the following questions:

   Why is testing required?
   What property change(s) are monitored?
   How often should testing be done?
   What results are sought?

What specimen dimensions are specified?
Where are specimens located?

MATERIALS

10 pieces of ductile iron wire (6" long).
1 irradiation source.
1 micrometer.
1 section of pipe (5" diameter, with wall thickness no greater than 1/8").
1 austenitic stainless steel specimen (with hardness of 350 to 420 Bhn).
1 garden hose.
Ice water (various temperatures).

PROCEDURES

EFFECT OF IRRADIATION ON METAL

1. Select ten pieces of a ductile wire.
2. Irradiate the ten pieces at different integrated flux levels in a nuclear reactor, as directed by instructor; record requested information on Data Table 15-8-1.
3. Measure tensile strength of each piece.

4. Plot tensile strengths as a function of integrated neutron flux; explain effect of irradiation on strength. What does this data suggest concerning reactor components made of this material?
5. List five materials not used in reactors because of adverse effects when exposed to radiation.

EFFECT OF TEMPERATURE ON MATERIAL

(Instructor should conduct this demonstration of the effects of temperature on brittleness or ductility.)

1. Cut up an ordinary plastic garden hose into 1-foot sections.
2. Cool each hose section at different temperatures in 5°F increments down to below freezing (that is, have one hose at 70°F, one at 65°F, one at 60°F and so on down to about 0°F) if possible.
3. Leave hose sections at their respective temperatures for 15 minutes (until thermal equilibrium is reached).
4. Hold each hose section by its ends; bend it into a U-shape; note difficulty of bending.
5. Repeat for all sections; note highest temperature at which a section failed. To what extent and why did each section fail?

DATA TABLE

DATA TABLE 15-8-1

Type of wire: ______________________________

Diameter: ____________ ins. (measured with micrometer)

Cross-sectioned area = $\frac{\pi}{4D^2}$ = ________________ sq. ins.

Sample Number	Irradiation Time	Integrated Flux	Force to Break Wire	Tensile Strength
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				

Test comments:

REFERENCE MATERIALS

Title 10, Part 50 of Code of Federal Regulations, Domestic Licensing of Production and Utilization Facilities, 1979.

Boyd, C.M., ed. Brittle Fractures in Steel Structures. Reading, MA: Pure-Butterworths and Co., 1970.

Gillet, H.W. The Behavior of Engineering Metals. New York: John Wiley and Sons, 1957.

Gilman, J.J. and Johnston, W.G. Dislocations and Mechanical Properties of Crystals. New York: John Wiley, 1957.

ASME Boiler and Pressure Vessel Code, an American National Standard, Section III, Subsection NB, Class I, Components.

Wilkinson, W.D. and Murphy, W.F. Nuclear Reactor Metallurgy. Princeton, NJ: D. Van Nostrand, 1958.

Wilson, J.C. Effects of Irradiating on the Structural Materials in Nuclear Power Reactors, Vol. 5. Geneva: 2nd International Conference on Peaceful Uses of Atomic Energy, 1958.

TEST

Read each question carefully and give the specific information required by the question. Your answers should be brief. Use the back of the test if you need additional space.

1. According to the Griffith theory of crack growth and nucleation, at what point does the critical stress for crack growth become catestrophic?

2. According to Griffith's theory, what causes a crack to begin to grow?

3. Define what is meant by a brittle fracture.

4. List the three conditions necessary for a brittle fracture to occur.

   (a)

   (b)

   (c)

5. Explain what is meant by RT_{NDT}.

6. List the impact tests which must be performed to determine RT_{NDT}.

7. How do radiation effects change the structure of a metal?

8. Explain how RT_{NDT} shifts with fast neutron fluence.

9. Explain why the shift in RT_{NDT} due to fast neutrons is sensitive to the copper content.

10. What effect does radiation have on the following mechanical properties of metals: yield strength, tensile hardness, brittleness?

11. What effect does radiation have on the results of impact tests done on carbon steels?

12. What effect does radiation have on a metal's yield point? On a metal's ductility?

13. What is the purpose of radiation annealing and thermal annealing?